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Infrared Experiments for Spaceborne Planetary Atmospheres Research

Full Report

Infrared Experiments Working Group

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Infrared Experiments for Spaceborne Planetary Atmospheres Research

Full Report

Infrared Experiments Working Group
Jet Propulsion Laboratory
Pasadena, California

National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

1981

II

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PREFACE

Experiments conducted in the infrared spectral region provide a powerful tool for the study of the composition, structure and dynamics of planetary atmospheres. However, the field has become highly complex, especially that part associated with spacecraft sensing, and the range of technologies used so diverse that it is difficult to determine which of the available methods for making a particular measurement is to be preferred, even for those deeply involved in the field.

Unfortunately, the realities of the age demand that some selectivity be employed; not all approaches can be supported. Furthermore, the chosen methods are generally sufficiently untried that long pre-flight developments are necessary if viable proposals are to be written for future flight opportunities. These considerations clearly lead to a program of developments which must be coordinated on a national scale. Accordingly, Dr. Robert E. Murphy, the Discipline Scientist for Planetary Atmospheres in the Office of Space Science at NASA Headquarters, requested early in 1980 the formation of an advisory group of specialists in the field. Called the Infrared Experiments Working Group, its function was:

1) To evaluate the role of 0.5-300 micron remote sensing in planetary atmospheres exploration;

2) To identify key areas of infrared instrumentation requiring development for the investigations of atmospheres ;

3) To provide the Planetary Programs Office with a framework within which such developments might be undertaken;

4) To document the state-of-the art.

The approach used was to assess the value of a broad range of measurement techniques for the investigation of atmospheric phenomena, including quantitative intercomparisons of existing and planned instruments by a phenomenological method: given a particular measurement goal (e.g., composition and abundance, temperature structure, cloud and aerosol, etc.), what technique could, if properly developed, investigate the phenomenon? The charter of the group was limited to consideration of space-borne and planetary probe instrumentation, principally for atmospheric investigations. The applicability of such instrumentation to the study of surfaces, comets and extended atmospheres was, however, included.

Agreeing to serve as members of the group were:

Reinhard Beer, Jet Propulsion Laboratory, Chairman
Daniel J. McCleese, Jet Propulsion Laboratory, Vice-Chairman
Jerome Apt, Jet Propulsion Laboratory, Secretary
Dale P. Cruikshank, University of Hawaii
C. B. Farmer, Jet Propulsion Laboratory

Uwe Fink, University of Arizona
J. Gille/M. Coffey/W. Mankin (alternates), National Center for Atmospheric Research
R. Hanel, NASA Goddard Space Flight Center
Andrew P. Ingersoll, California Institute of Technology
Barry Lutz, Lowell Observatory
Michael E. Mickelson, Denison University
Michael J. Mumma, NASA Goddard Space Flight Center
Alan T. Tokunaga, University of Hawaii
Martin G. Tomasko, University of Arizona
Laurence M. Trafton, University of Texas
Wesley A. Traub, Smithsonian Astrophysical Observatory
Fred C. Witteborn, NASA Ames Research Center

The group met on four occassions:

February 5-6, 1980 at JPL
May 6-7, 1980 at JPL
July 15-16, 1980 at JPL
September 16-17, 1980 at Goddard Space Flight Center

The group functioned by preparing internal working papers addressing each phase of the study which were then reviewed at length at the meetings. These papers were written by the working group members, who sought additional material on specific topics from the following individuals whose contributions we wish to acknowledge: R. Carlson, T. Gehrels, D. Hinkley, R. J. Huppi, H. P. Larson, R. Menzies, G. S. Orton, S. W. Petrick, and A. T. Stair.

The group has tried to avoid suggesting which scientific investigations ought to be pursued for the various atmospheres. Rather, we examined each of the phenomena which might be investigated by infrared techniques, determining whether a substantial contribution could be made in the infrared and if so providing criteria for the accuracy, time scale, and other parameters which would be required to advance current knowledge. The discussion of the phenomena and the criteria for their measurement comprise Chapter I. Chapter II is an overview of existing infrared techniques and their achieved performance. In order to compare proposed techniques for investigating the various phenomena we performed detailed analyses of the techniques for selected cases. These appear in Chapter III together with discussions of the critical items requiring development for each technique. Additional discussions of critical technologies appear in Appendix A. The detailed assessments defined both the optimum strategies for investigating the phenomena and the developments required for their implementation. Both the technical conclusions emerging from these studies and the recommended development program appear in Chapter IV. Some strategies require little development; their omission from the recommended development program indicates that proposals for flight hardware can be written within the current state-of-the-art.

INFRARED EXPERIMENTS WORKING GROUP

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The Infrared Experiments Working Group has summarized its deliberations in the form of specific conclusions and recommendations after a thorough review of the scientific and technological material.

A. CONCLUSIONS

Conclusion 1: Infrared Remote Sensing

The infrared spectrum is of key importance for the remote investigation of the following phenomena in planetary atmospheres:

- Global and local radiative budget
- Radiative flux profiles
- Winds
- Temperature and pressure
- Planetary rotation and global atmospheric activity
- Abundance of stable constituents
- Vertical, lateral, and temporal variability of species
- Radiative properties of clouds and aerosols
- Cloud macrostructure and microstructure
- Non-LTE phenomena

Conclusion 2: Infrared In-Situ Sensing via Entry Probes

Infrared techniques are of key importance in the investigation by entry probes of:

- Radiative flux profiles
- Detection, abundance, and vertical distribution of species
- Properties of clouds

Conclusion 3: Requirement for Utilization of Near-Earth Orbital Platforms

Some experiments can be performed better from Earth orbit than from a planetary orbiter or flyby. These include high-resolution spectroscopy for the detection of low abundance species and long-term monitoring of the variability of other key compositional and physical parameters. Support is required from the Planetary Office for utilization of SIRTF, Space Telescope, and the Shuttle for planetary infrared research.

Conclusion 4: Requirement for Instrument Development Program

Significant progress beyond the current state of development of spaceborneinfrared instrumentation requires a stable and diverse instrument development program which supports, over the long term, developments in techniques and hardware.

Specific areas of instrumentation and technology which will significantly advance infrared planetary investigations are identified below.

Conclusion 5: Requirement for Supporting Studies

Expanded spectroscopy and other laboratory studies are required. Long term and vigorous support of theoretical studies concerning instrument concepts and data analysis techniques is needed.

B. RECOMMENDATIONS:

We have considered in detail the requirements for the investigation by infrared techniques of the phenomena listed in conclusion 1 and conclusion 2. Instruments for probes, flybys, planetary orbiters, and near-Earth facilities are each important parts of a balanced planetary exploration program; thus the order of recommendation does not denote priority. We recommend:

- That support be given for the development of high and ultra-high resolution planetary infrared spectrometers for Earth orbiting telescopes. Spectrometers which resolve pressure broadened lines and spectrometers which resolve Doppler broadened line cores are required.

- That support be given to the development of gas correlation spectrometers for the study of physical and species-specific chemical properties of planetary atmospheres.

- That support be given for the utilization of infrared detector arrays in low to intermediate spectral resolution cryogenic IR imaging systems.

- That support be given to the design of a high resolution solar occultation spectrometer for survey investigations of the minor and trace components of atmospheres. Such an instrument can provide high sensitivity for the detection of constituents above cloud layers.

- That studies be initiated to define the required characteristics of a probe/in situ planetary infrared spectrometer for detection and measurement of composition as a function of height below cloud level. An instrument of this type would add significantly to the science return from a probe instrument set.

- That studies be initiated to improve substantially the state of the art of on-board radiometric calibration of reflected solar and thermal flux.

CHAPTER I: THE ROLE OF INFRARED SENSING IN ATMOSPHERIC SCIENCE

Introduction

Since the beginning of the modern era of planetary exploration, infrared observation has played an important part in the study of both atmospheres and surfaces. The power of the technology lies in its extreme versatility. It can be used to study such diverse properties as the global and local energy balance of a planet, the abundance and distribution (in 3 dimensions) of atmospheric constituents down to parts per billion or less, the nature and distribution of clouds, the variation of temperature and pressure with altitude, velocities and gross atmospheric motions, the nature and distribution of non-equilibrium phenomena (for instance: lightning, charged particle influx, meteorite influx and photochemistry), surface temperatures and surface geology.

Atmospheric Phenomena Investigated by Infrared Instruments

The potential list of atmospheric phenomena is very large and no claim is made that the list presented below is exhaustive. To complicate matters further, for most phenomena there are several means of investigation available, by no means all infrared. Furthermore, it was essential for us to avoid a number of pitfalls:

(1) The role of a working group is advisory. Therefore, the evidential materials presented in this and later chapters are to be considered as illustrations not proposals.

(2) It was essential to avoid ranking phenomena and techniques, even though we were well aware that the mere act of inclusion implies an inherent prioritization.

(3) Since our role was to consider experiments, not missions, we were constrained to assume that any mission is possible, however unlikely. In fact, we went to some lengths to try to operate in a mission-independent manner. Nevertheless, we were well aware that some experiments can be performed only on a specific type of mission (e.g., Earth-orbiting, planetary flyby, planetary orbiter, spin-stabilized or 3-axis stabilized spacecraft, entry probe, etc.) and our final conclusions and recommendations recognize this fact.

In addition to the foregoing constraints there was one more that the group imposed on itself: that we would be, as far as possible, quantitative rather than qualitative. In this manner, we hoped to avoid subjective judgments when we compared two techniques or approaches. For the phenomena discussed below, then, we attempted to lay down measurement requirements.

The values quoted represent the best judgment of the group and were used in all subsequent discussions. Some of the requirements are very stringent and incapable of being met by any technique known to us. Nevertheless, we felt it to be important to set out numerical criteria, usually in the form of "acceptable" and "desirable"values where this was possible. Attainment of "acceptable" criteria would lead to new knowledge about a planet; a "desirable" result would lead to a definitive solution of the problem (that is, answer all identifiable questions).

The phenomena to be discussed are:

(1) Global and Local Radiative Budget

(2) Radiative Flux Profiles

(3) Winds

(4) Temperature

(5) Pressure

(6) Transient and Marginal Atmospheres

(7) Planetary Rotation and Global Atmospheric Activity

(8) Abundances of Stable Constituents

(9) Vertical, Lateral and Temporal Distribution of Abundances

(10) Composition of Clouds and Aerosols

(11) Radiative Properties of Clouds and Aerosols

(12) Cloud Microstructure

(13) Cloud Macrostructure

(14) Non-LTE Phenomena

For each phenomenon we have included a discussion of its nature, importance and, where relevant, the means by which infrared experiments have contributed to the understanding of the phenomenon. Each one is followed by a table of measurement requirements. Of these, the most controversial are likely to be the spatial and temporal resolution requirements but it must be recognized that we were looking to the future when we hope to obtain new information, not merely re-hash the old.

(1) Global and Local Radiative Budget

a) Global Radiative Budget

Measurement of the global radiative budget is important for establishing the magnitude of the internal heat source for each planet. This quantity bears on the internal structure of the planet (by providing a boundary condition to interior models) and on its origin and evolution. It may help to answer questions such as: Is the planet still cooling from its primeval condensation? Are phases of different density separating? Is tidal heating important? Is radioactive heating significant? Radioactive heating is expected to melt the interiors of the icy satellites and tidal heating of Io is strong enough to supply the energy required to drive Io's volcanos.

Only a portion of the incident sunlight is diffusely reflected by a planet; the rest is absorbed and radiated as heat along with the heat from any internal source. In order to derive the magnitude of the internal heat source, it is necessary to measure the thermal radiation of the planet and to measure the amount of sunlight reflected by the planet. The insolation is known, therefore the portion of the thermal flux due to absorbed sunlight may be calculated and the portion due to the internal heat source deduced.

The thermal radiation of some planets depends significantly on latitude and longitude. For example, the dark side of a slowly rotating body, like the Earth's moon, is considerably cooler than the sunlit side and the polar regions of a planet such as Earth or Mars are often significantly cooler than their equators. Therefore, the thermal radiation is not spherically symmetric and measurements should to be made at a variety of solar phase angles, planetary latitudes and longitudes.

Planets with thick atmospheres have very long radiative time constants so that the day-night difference in the thermal emission may be neglected. However, the latitudinal variation may be significant for those planets which do not have a large internal heat source. For Jupiter, the internal heat flux is several times the insolation flux, the atmosphere is very thick and the rotation period is short. Furthermore, the obliquity is slight and the orbit approximately circular so that seasonal variations in the thermal flux are slight and a single measurement of the thermal flux would suffice. On the other hand, Uranus, which also has a thick atmosphere, has little or no internal heat source and a very large obliquity. Seasonal effects and latitudinal variation in the thermal flux may be quite pronounced, depending on the magnitude of meridional heat transport in the atmosphere.

Measurement of the global thermal emission of cometary nuclei is especially difficult because of the rapid temperature variation as the comet approaches the Sun and the sporadic and spatially asymmetric character of outgassing subliming volatiles.

In addition to the bolometric thermal flux, it is necessary to measure the entire solar flux diffusely reflected by the planet in order to derive the Bond (spherical albedo) and the magnitude of any internal heat source. Since the solar spectrum extends far into the ultraviolet where it varies rapidly with wavelength, it is necessary to make such measurements from outside the Earth's atmosphere. The angular distribution of the scattered intensity is also a useful tool for the measurement of the aerosol-particle makeup and distribution in the atmosphere.

b) Local Radiative Budget

Measurement of the local radiative budget is important for studying meteorology and seasonal effects, and for understanding spatial features like belts, zones and ovals in a planetary atmosphere; such studies on other planetsare still rudimentary. The best results obtained so far are from the Viking Mars orbiters and landers, which have made synoptic observations over a period of many months. Venus entry probes have attempted to measure the solar flux as a function of depth in the atmosphere and ground-based spectroscopy has revealed seasonal phenomena on Mars and Saturn. Long-term albedo changes are apparent for Titan, Uranus and Neptune. Short-term changes have been observed for H_2O and CO_2 absorption in Venus' atmosphere, H_2O in Mars' atmosphere (from occasional dust storms) and CH_4 in Neptune's atmosphere. These are probably all correlated with changes in the clouds and hazes - changes possibly involving the local radiative balance.

Global and Local Radiative Budget

Measurement Requirements

Object	Venus	Uranus
Accuracy	0.5% (3%)	1% (5%)
Precision	0.2% (2%)	1% (5%)
Time Constant	10 min (1 hr)	5 min (10 min)
Sampling Interval	10 min (1 day)	3 yrs (10 yrs)
Time Base	1 planet year	1 planet year
Resolution:		
Hor.	R/30 (2R)	R/10 (2R)
Vert.	---	---

NOTES:

1) Parentheses enclose "acceptable" values
2) R = planetary radius
3) Data are typical for inner and outer planets

(2) Radiative Flux Profiles

In addition to knowing the balance between absorbed sunlight and emitted thermal radiation for the planet as a whole, it is important to understand the variation in both of these quantities with depth in the atmosphere. For every layer of the atmosphere, the excess of thermal energy radiated over thermal energy absorbed must be provided by the sum of the solar energy absorbed in the layer, the work done on the layer by dynamical processes and the chemical (such as latent heat) or other energy released in the layer. Comparison of the profiles of thermal energy emitted and solar energy absorbed indicates the extent to which other processes such as dynamics or latent heat transfer are responsible for the heat balance of the atmosphere.

The net (downward minus upward) solar flux measured at each altitude gives the total solar energy absorbed below that level of the atmosphere. The difference in the net solar flux at two altitudes gives the solar energy absorbed in the intervening layer. Similarly, the divergence in the net thermal flux gives the rate at which thermal energy is being lost by the layer. Direct measures of the profiles require entry probes and so far (except for the Earth) have been made only for Venus. Measurements of the solar and thermal flux profiles are planned for Jupiter by the Galileo mission.

Interpretation of the thermal net flux measurements on Venus has proven to be very difficult (Tomasko, et al, 1980). The thermal net flux in the lower atmosphere was observed to differ by more than a factor of 3 from place to place on the planet, while the temperature structure was very uniform. At some locations on the planet the thermal fluxes were measured to be several times larger than the globally averaged solar net flux. A number of explanations have been put forth for these observations, including instrumental errors of various types, but as yet, no consistent picture has emerged.

The solar net flux profiles were somewhat easier to interpret largely because the difference between the upward and downward fluxes is generally more than 10-15 percent of either one, as opposed to the typically 1 percent difference between the upward and downward thermal fluxes. Nevertheless, heretofore unfamiliar systematic effects such as the presence of cloud particles on the windows can compromise the measurements. Further, for thin or broken clouds, care must be taken with the fields of view of the instrument to allow for the direct solar beam and reflections from parts of the spacecraft.

Radiative Flux Profiles

Measurement Requirements

Object	All
Accuracy	2% (10%)
Precision	2%
Time Constant	~msec
Sampling Interval	~msec
Time Base	---
Resolution:	
Hor.	---
Vert.	H/10 (H/3)

NOTES:

1) Parenthesis enclose "acceptable" values
2) H = atmospheric scale height

(3) Winds

Measurements of the components of the atmospheric circulation, i.e., the winds, are essential to an understanding of the mass transport, the atmospheric heat budget, and the climatology of planetary atmospheres.

To date, our knowledge of atmospheric circulation for all planetary atmospheres, including the Earth, has been derived from *in situ* measurements, from inferences from remotely sensed temperature fields, from cloud tracking and by ground-based Doppler-shift spectroscopy. Experience gained from the study of Earth's atmosphere shows that global coverage, not possible with probes, is a fundamental requirement for wind sensing. Inference of winds from remote sensing of the temperature and pressure is limited by:

(1) assumptions of geostrophy or of other balance relationships between the mass and wind fields; geostrophy does not hold in planetary equatorial regions and even more sophisticated balance models suffer in that small errors in measurements of the pressure (temperature) field can lead to large errors in the deduced wind field.

(2) the requirement that a temperature *field* (local field for geostrophic computations; nearly global field for more elaborate balance models) be measured to permit computation of the winds.

(3) together, (1) and (2) imply that winds associated with rapidly changing events, e.g., the great dust storms on Mars, and other transient phenomena cannot be accurately deduced.

(4) boundary conditions (especially topographic) must be specified in order to infer winds from temperature data.

The technique of cloud tracking to deduce winds is limited to atmospheric layers containing long lived features in an inhomogeneous cloud field.

Attempts to deduce the wind field above 60 km in the atmosphere of Venus utilizing the combined data from cloud tracking and temperature sounding have been only partially successful for the reasons outlined above. Similar problems can be anticipated in deducing winds in this way for the outer planets. On Mars, the variable terrain greatly complicates specification of proper boundary conditions.

It follows, then, that only techniques that utilize Doppler measurements might be expected to produce wholly satisfactory results. In turn, this requirement implies spectroscopic techniques of high to very high spectral and spatial resolution.

Winds

Measurement Requirements

Planet	Venus/Mars	Outer Planets/Titan/Io
Accuracy	2 m/s (10 m/s)	2 m/s (10 m/s)
Precision	1 m/s (5 m/s)	1 m/s (5 m/s)
Time Constant	1 min (1 hr)	1 min (1 hr)
Sampling Interval	1 hr (1 day)	1 hr (1 day)
Time Base	≥ 1 planet year	≥ 15 yr (1 yr)
Resolution:		
Hor.	R/60 (R/10)	R/60 (R/10)
Vert.	H/3 (1 H)	H/3 (1 H)

NOTES:

1) Parentheses enclose "acceptable" values
2) R = planetary radius
3) H = atmospheric scale height

(4) Temperature

Temperature is probably the most fundamental parameter defining the state of an atmosphere or surface. Knowledge of the temperature structure of a planetary body is essential to understanding its thermal balance and the physical/chemical structure and dynamics of its atmosphere. Thus the measurement of temperature, either by remote sensing or *in situ* methods, has been a basic capability required of the instrument payload of virtually every planetary mission. The rationale for continued refinement of measurements of temperature is based as much on the indispensible role the measurements play in the interpretation of morphological and compositional observations as on the direct description of the physical state which they give.

Apart from the detailed and localized vertical profiles of temperature for Mars and Venus obtained from atmospheric entry probes, most of the present day knowledge of planetary atmospheric and surface temperatures has come from measurements using remote sensing methods at infrared and microwave wavelengths. The remote sensing methods are of particular importance in that they provide the only practical means of obtaining global coverage. Both direct and indirect methods of determining temperature from infrared measurements are used. The "direct" methods are those in which the surface or atmospheric outgoing radiation is measured and interpreted directly (through the Planck function) as temperature; the "indirect" methods are those in which some temperature dependent property, such as the distribution of rotational line intensities within the band structure of the spectrum of a molecular constituent, is used to infer the atmospheric temperature.

While the theoretical basis of the infrared remote sensing methods (i.e., radiative transfer in a homogeneous atmosphere) is fairly well understood, in practice a number of problems limit the use of the methods and the reliability of the derived temperatures. These difficulties include the effects of partial cloud cover on the clear atmosphere radiance values, the limitation in vertical resolution (of about one scale height) for the case of nadir sounding, and the poor spatial resolution and precision associated with measurements of low temperature atmospheres (outer planets). The microwave methods, while less susceptible to problems of clouds, have their own difficulties of interpretation and the most prominent, radio occultation, provides only sporadic coverage.

Temperature

Measurement Requirements

Object	Atmosphere	Surface
Accuracy	1 K (3 K)	1 K (3 K)
Precision	0.5 K (1 K)	0.5 K (1 K)
Time Constant	1 min (1 hr)	1 min (1 hr)
Sampling Interval	1 hr	1 hr
Time Base	2 planet years (1 planet year)	5 planet years (1 planet year)
Resolution:		
Hor.	R/60 (R/10)	1 km
Vert.	H/3 (1 H)	---

NOTES:

1) Parentheses enclose "acceptable" values
2) R = planetary radius
3) H = atmospheric scale height

(5) Pressure

Pressure is a fundamental datum for the description of any atmosphere and is related, *via* the gas law

$$\mu P = \rho RT$$

to the temperature T, the mean molecular weight μ and the density ρ. Since there exist independent means for inferring or estimating μ and T, it follows that the density ρ can be extracted. In turn, the density is an important input to studies of heat transport, chemical kinetics and condensation phenomena. However, it must be emphasized that is is crucial to know P *vs* Z, the altitude (even though Z can often only be defined with respect to an arbitrary zero) because the vertical variation of density has important repercussions on many of the phenomena discussed in this chapter. For example, at low densities, convective heat transport becomes ineffectual and thermochemistry gives way to photochemistry. In addition, spectral line broadening, which in lower atmospheres is dominated by pressure effects, becomes increasingly determined by the temperature the lower the pressure becomes. Is is no coincidence that most infrared remote sensing techniques "see" at best only a little below the convective/radiative boundary (the tropopause) and visible/UV radiation rarely even that far. In a troposphere, both pressure and density increase rapidly so that spectral absorption increases both from the greater gas column and from the effect of pressure broadening. Consequently, the opacity (even in the "continuum") eventually becomes total even in the absence of clouds and knowledge of deeper levels can be inferred only indirectly. It is evident that the run of pressure with altitude is a critical phenomenon that should be addressed by as many experiments as possible. In addition, the lateral variation of this profile is a primary ingredient to meteorological studies.

Pressure at one or a few points can be measured directly from slow-moving entry probes (i.e., ones that produce no substantial pressure-wave from their own motion) and, indeed, entry probes offer the only means of determining an absolute pressure *vs* height profile. Given such a baseline, remote sensing measurements can extend these spot measurements to a global scale by an examination of the effect of pressure on the shape of the spectral lines. At low resolution, curve-of-growth analyses provide some information. At resolutions comparable to the line widths, spectrum synthesis gives better results but for the most complete analysis, line profiles must be investigated either by very high resolution spectroscopy or by correlation spectroscopy. Again, microwave occultation experiments offer a quite direct measurement of density but the coverage is sporadic in time and space.

Pressure

Measurement Requirements

Object	Terrestrial	Outer
Accuracy	0.5% (1%)	1% (10%)
Precision	0.2% (0.5%)	0.5% (5%)
Time Constant	1 min (1 hr)	1 min (1 hr)
Sampling Interval	1 hr	1 hr
Time Base	5 planet years (1 planet year)	1 planet year (1 year)
Resolution:		
Hor.	R/60 (R/10)	R/60 (R/10)
Vert.	H/3 (1H)	H/3 (1H)

NOTES:

1) Parentheses enclose "acceptable" values
2) R = planetary radius
3) H = atmospheric scale height

(6) Transient and Marginal Atmospheres

Most of the large bodies in the solar system have detectable atmospheres, but there are a few ambiguous cases, such as Pluto and Mercury. Other bodies, such as the largest asteroids, the Galilean satellites, and extinct cometary nuclei may have tenuous atmospheres so far undetected. The detection of atmospheres on such bodies constitutes a significant scientific problem related to their formation and evolution.

The atmosphere of Mercury at the planet's surface has properties inferred from measurements of the upper atmosphere by Mariner 10 (Broadfoot 1976). Helium and hydrogen were discovered, and an upper limit to the total surface pressure of $1\text{-}2 \times 10^{-9}$ mbar was found from the occultation spectrometer experiment. Upper limits to the concentrations of noble gases and other constituents resulted from the airglow spectrometer observations. Direct detection of any constituents other than helium and hydrogen would be of great interest as an index of the present outgassing of the planet.

The presence of an atmosphere on Pluto is inferred from the observations of solid methane on the surface (Cruikshank et al. 1976, Cruikshank and Silvaggio 1980, Soifer et al. 1980), and Trafton (1980) has shown that all the methane will be lost unless some heavier gas is there to bind the methane to the planet. The heavier gas may be a noble gas. There is no direct spectroscopic evidence of gas absorption on Pluto.

Europa, Ganymede, and Callisto have surface exposures of water frost and ice, and by vapor pressure considerations they should have tenuous atmospheres,though none have so far been detected. Noble gases may occur in the tenuous atmospheres of these bodies.

The largest asteroids are, in principle, capable of retaining tenuous atmospheres of heavy gases, though none have so far been found. Some of the bodies have minerals containing water of hydration (bound water), though this will not contribute to a potential atmosphere of water vapor or other gases. No surface exposures of frozen volatiles have been detected on any asteroid.

At least four of the five Uranian satellites (all but Miranda) are known to have surfaces composed of water ice or frost (Cruikshank 1980, Nicholson and Jones 1980). The vapor pressure of water at the expected temperatures of these bodies is on the order of 10^{-9} mbar, but heavier gases may constitute a more substantial atmosphere.

A study of the orbital elements of asteroids and short-period comets show that there is a clear distinction in terms of semi-major axis and eccentricity. There are a few cases of overlap, however, such as asteroids 944 Hidalgo and 1979 VA. In an approach to the fundamental problem of the interrelation of the comets and the asteroids, some preliminary searches for cometary activity on asteroids have been made, so far without success (Degewij 1980). It remains important, however, to search for atmospheres or evidence of cometary activity on asteroids having orbital parameters indicative of their possible origins as comets.

Transient and Marginal Atmospheres

Measurement Requirements

Object	All
Accuracy	10%
Precision	10%
Time Constant	1 sec (1 min)
Sampling Interval	Repetitive measurements desirable
Time Base	
Resolution:	
Hor.	2 R
Vert.	---

NOTES:

1) Parentheses enclose "acceptable" values
2) R = planetary radius

(7) Planetary Rotation and Global Atmospheric Activity

The rotation periods of some bodies have proved difficult to determine by either spectroscopy or photometry. The inclination of spectral lines resulting from the differential Doppler shift is small and difficult to measure, and the light curves at visible wavelengths resulting from longitudinal (zonal) brightness differences on these objects show a very small amplitude as they rotate.

The discovery by Joyce et al. (1977) that Neptune is sometimes unexpectedly bright and somewhat variable at near-infrared (1.2 - 3.6 μm) wavelengths, together with the subsequent JHK photometry of the planet by Cruikshank (1978), showed that a zonal structure is present in the planet's atmosphere. It appears that JHK photometry can reveal the rotation period of the planet's atmosphere in the region where strong infrared absorptions due to methane are formed because of the sensitivity of Neptune's reflected sunlight spectrum to small variations in the apparent concentration of the absorbing gas. Similarly, the near-infrared spectrum of Uranus is dominated by methane absorptions, and near-infrared photometry or spectrophotometry of this planet can yield information on the rotation period of the upper atmosphere. The planet must be spatially resolved from the ring system because the latter has a near-infrared flux at JHK comparable to that from the planet.

Ground-based JHK photometry of Titan (Cruikshank and Morgan 1980) has shown that this object is variable on a time scale of days. While the solid body of Titan is expected to be locked in rotation to its period of revolution around Saturn, the upper atmosphere, also dominated by methane, is not necessarily perfectly coupled to the satellite. The variability may thus represent rotation of the upper atmosphere with a period or characteristic time scale different from the satellite's 16-day period, or it may represent changes in the global atmospheric activity; the existing data base is insufficient for a clear understanding of the phenomenon.

The rotation periods of both Triton and Pluto are apparently known from photometry, but continued infrared observations may reveal information about the global scale of any variability in their atmospheres. Indeed, there is presently marginal evidence (Cruikshank et al. 1979) for variability of the spectrum of Triton; if it proves to be correct, monitoring of the satellite in the infrared will provide valuable information on the nature of this body.

Thus, photometric observations of Neptune, Uranus, and Titan, with the possible addition of Triton and Pluto, can be used to determine the rotation periods of these bodies or at least the characteristic rotation periods of the upper atmospheres. In any case, continued monitoring by infrared photometry will yield a global index of such atmospheric activity as might occur.

Planetary Rotation and Global Atmospheric Activity

Measurement Requirements

Object	Uranus, Neptune, Triton, Titan, Pluto
Accuracy	5%
Precision	1%
Time Constant	30 min
Sampling Interval	30 min
Time Base	3 yrs (5 days)
Resolution:	
Hor.	2 R
Vert.	---

NOTES:

1) Parentheses enclose "acceptable" values
2) R = planetary radius

(8) Abundances of Stable Constituents

The search for and subsequent detection and determination of abundances of the constituents of planetary atmospheres (especially the outer planets) is of the utmost importance to our progress in unraveling the primordial composition of our solar system and to our understanding of its evolution to the present state.

The present state of our knowledge of the constituents of the outer planet atmospheres as obtained from the infrared spectrum is summarized in the first of the two accompanying tables.* Although the discovery of "new" major constituents is unlikely, improvements in detector sensitivities and instrument design and the opening of new spectral windows can almost certainly be expected to reveal minor and trace atomic, molecular, and ionic species not yet observed. Current upper limits of possible trace molecules are also suggested in Table I-1, as are some expected isotopic species of selected minor species.

As a bonus, the vertical distribution of atmospheric constituents as a function of height can be inferred from high-resolution spectroscopic studies. A primary datum for this study is the run of atmospheric pressures at line formation depths, and infrared molecular bands are ideally suited for this task. Since a single band of a given constituent has inherently a large dynamic range of line strengths, it enables us to probe a similarly large range of atmospheric pressures. Coupled with other bands having an even broader range of band strengths, an extensive set of pressures-versus-height distributions can be studied.

The basic observations required for a study of the vertical distribution of atmospheric pressure are not only line depths, but also line widths and, even more desirable, detailed line shapes within molecular bands. However, adequate supporting laboratory data are essential.

When these compositional studies are expanded to include "extended atmospheres" including such regions as the tenuous torus cloud around Io and the coma and tail of comets, the search and discovery program assumes a somewhat different orientation. In this case photochemical products become the dominant types to be studied, and the possibilities are greatly expanded. Table I-2 summarizes the current status of the discoveries and searches.

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*For the purpose of this study, the gross chemical abundances of the atmospheres of the terrestrial planets are assumed to be sufficiently well-known to require no new developments for such improvements as may seem desirable in the future.

Table I-1. Molecular Species in the Atmospheres of the Outer Planets: Detection and Upper Limits in the Spectral Region 0.5-300 μm

Molecule	Jupiter	Saturn	Titan	Uranus	Neptune	Employed Spectral Windows and (Other Possible Regions for Selected Molecules) (μm)
H_2	1	1	$2x10^{-3}$	1	1	0.6, 0.8, (2, 28)
HD	$2x10^{-5}$	$2x10^{-5}$		$1.5x10^{-5}$		0.6, 0.7 (0.5, 0.95, 1.5, 2.7)
D_2						
CH_4	$7x10^{-4}$	$5x10^{-4}$	$3x10^{-2}$			.5, .6, .7, .8, .9, 1.0, 1.3, 7.8,
$^{13}CH_4$	$7x10^{-6}$					1.0 (7.8)
CH_3D	$3x10^{-7}$					4.5 (0.8, 1.0, 1.6)
$^{13}CH_3D$						4.5 (0.8, 1.0, 1.6)
NH_3	$2x10^{-4}$	$3x10^{-5}$	$<2x10^{-5}$	$<1.2x10^{-7}$	$<5x10^{-7}$	0.55, 0.65, 1.5, 2.3, 3.0, 6.1, 11
$^{15}NH_3$	$1x10^{-6}$					11, (0.65, 1.5)
NH_2D						11
C_2H_6	$4x10^4$	detected	$2x10^{-5}$		$<1x10^{-7}$	12 (7)
$^{13}CCH_2$						12 (7)
C_2H_5D						?
C_2H_2	8x10-5	$<1.4x10^{-7}$	$5x10^{-6}$	$<5x10^{-8}$	$<3x10^{-7}$	14 (1.0, 1.2, 5.0)
$^{13}CCH_2$						14 (1.0, 1.2, 5.0)
C_2HD						(1.0, 3.0, 5.4, 15, 19)
C_2H_4			$8x10^{-7}$			10.5
H_2O	$1x10^{-6}$					5 (1.1, 1.4, 2.6, 2.7)
HDO						(1.1, 3.7, 7.1)
PH_3	$1-4x10^{-7}$	$1x10^{-6}$				5, 10
CO	$2x10^{-9}$					5
^{13}CO						5
GeH_4	$6x10^{-10}$					5
H_2S	$<5x10^{-5}$	$<1-4x10^{-6}$	$<3x10^{-4}$	$<8x10^{-7}$	$<3x10^{-6}$	5 (2.6)
C_3H_8	$<5x10^{-6}$		$3x10^{-5}$			5, 13.4

Table I-1. (continued)

Molecule	Jupiter	Saturn	Titan	Uranus	Neptune	Employed Spectral Windows and (Other Possible Regions for Selected Molecules) (μm)
$C_2H_5NH_2$	4×10^{-6}					5
HCN	$<1\times10^{-6}$		5×10^{-7}			14
CH_3CN	$<3\times10^{-6}$					5
CH_3	$<2\times10^{-6}$					5
HCN	$<1\times10^{-6}$					5
CH_2NH_2	$<6\times10^{-7}$	$<3\times10^{-7}$	$<5\times10^{-5}$	$<3\times10^{-7}$	$<3\times10^{-7}$	
$(CH_3)_2NH$	$<6\times10^{-7}$					5
CO_2	$<2\times10^{-7}$					4.2 (1.7, 2.8, 7.2, 7.8)
$(CH_3)_2O$	$<2\times10^{-7}$					5
C_3H_4			6×10^{-8}			15.8, 30.8
C_3H_6	$<1\times10^{-7}$					5
CH_3OH	$<1\times10^{-7}$	$<1.4\times10^{-6}$	$<3\times10^{-4}$		$<5\times10^{-7}$	5
N_2O	$<3\times10^{-8}$		$<1\times10^{-4}$		$<8\times10^{-7}$	5
C_2H_4	$<3\times10^{-8}$	$<1.4\times10^{-6}$	$<3\times10^{-4}$	$<5\times10^{-7}$	$<5\times10^{-7}$	5
$CH_2\text{-}C\text{-}CH_2$	$<8\times10^{-9}$					5
AsH_3	$<4\times10^{-9}$					5
SiH_4	$<2\times10^{-9}$					5
COS		$<1.4\times10^{-6}$		$<2\times10^{-4}$	$<5\times10^{-7}$	5

Table I-2. Spectroscopic Species and Extended Atmospheres: Detections and Upper Limits and Unsuccessful Searches in the Spectral Range 0.5-300 μm

Molecule	Object of Search	Abundance	Spectral Region (μm)
SO_2	Io	0.2 cm-atm	7.4
COS	Io	$<3.8\times10^{-4}$ cm-atm	12
CS_2	Io	$<3.5\times10^{-5}$ "	6.5
SO_3	Io	$<6.5\times10^{-5}$ "	20
H_2S	Io	7×10^{-2} "	Occultation
CO_2	Io	$<1.5\times10^{-4}$ "	15
O_3	Io	$.9\times10^{-3}$ "	9.6
N_2O	Io	$<7.4\times10^{-3}$ "	17
H_2O	Io	$<9.2\times10^{-3}$ "	39
CH_4	Io	$<1.0\times10^{-3}$ "	7.8
NH_3	Io	$<1.4\times10^{-3}$ "	11
HC	Io	$<3.8\times10^{-3}$ "	49
Na	Io	10^{10}-10^{11} cm^{-2}	0.6
S^+	Io	Detected	0.7
CN	Cometary coma	Detected	0.8-1.1
C_2	Cometary coma	Detected	0.5-0.8
NH_2	Cometary coma	Detected	0.6-0.7
H_2O^+	Cometary coma	Detected	0.6
H_2	Cometary coma	Not detected	2.8
CH_4	Cometary coma	Not detected	3.3
"Si"	Cometary coma	"Silicon signature detected"	10, 18
CH_2	Cometary coma	Not detected	0.5-0.9
HCO	Cometary coma	Not detected	0.7
HNO	Cometary coma	Not detected	0.7-0.8

Abundances of Stable Constituents

Measurement Requirements

Object	Outer Planets/Titan
Accuracy	1% (5%)
Precision	0.2% (1%)
Time Constant	---
Sampling Interval	---
Time Base	---
Resolution:	
Hor.	R/20 (2R)
Vert.	---

NOTES:

1) Parentheses enclose "acceptable" values
2) R = planetary radius

(9) Vertical, Lateral, and Temporal Distribution of Abundances

a. Vertical Distribution

The vertical variation of the relative abundance of species is an indicator of:

(1) the upward transport of deep atmospheric species;

(2) the downward transport of atmospheric species (especially photochemical products);

(3) condensation to the liquid or solid phase;

(4) the possible influx of extra-planetary material such as meteorites and satellite ejecta; and

(5) the presence of other disequilibrating phenomena such as photochemistry, lightning, ion-molecule reactions, etc.

Recent ground-based, airborne, and space observations of Jupiter and Saturn have shown that the chemical evolution of these planets is greatly affected by disequilibrium chemical processes such as those listed above (Larson, H. P. 1977). For example, C_2H_2, C_2H_6, CO, PH_3, and GeH_4 have been discovered on Jupiter although such gases are not predicted to be present in observable amounts on the basis of equilibrium chemistry. C_2H_2, C_2H_6, and CO are known to have non-uniform mixing ratios on Jupiter as a direct result of disequilibrium chemistry.

CO on Venus is also strongly height variable, increasing rapidly in the mesosphere, and providing a possible source of oxygen via the reaction

$$CO_2 + h\nu \longrightarrow CO + O$$

in a photochemical sequence.

Observation of minor constituents therefore provides a useful probe of the processes listed above. Such phenomena certainly occur on every planet having an atmosphere and greatly influence their chemical evolution.

b. Lateral Distribution

"Lateral distribution" is defined as the variation of abundance at a given pressure/temperature level. An obvious example of such lateral variation is the distribution of chromophores on Jupiter, a well-known and important problem having a bearing on the non-equilibrium chemistry of the planet. Other examples are the reported meridional variation of C_2H_2 and C_2H_6 by the Voyager IRIS (Hanel et al, 1979) believed to be caused by photochemical processes, and the finding by the Pioneer Venus OIR of significant lateral variation of a strong 50 μm absorber that appears to be solar-locked in the early Venus afternoon. (Taylor et al, 1980)

Of a somewhat different nature is the reported variation of SO_2 on Io. This clearly relates to the properties of the volcanic plumes, since the SO_2 is found to be concentrated near them.

These examples highlight the importance of such measurements: lateral variation of abundance is a direct consequence of the chemical sources and sinks within the atmosphere. Understanding of the lateral distribution of species will therefore help to answer questions such as: what is the origin of colors on Jupiter? How is the chemical evolution of a planetary atmosphere affected by the horizontal transport of gases by winds? What physical mechanisms affect the lateral distribution of gases?

c. Time Variability

In many cases it is difficult to separate true time variation of abundance from mass motion of a production source, limb darkening or from the uncovering of the source from a moving cloud or haze cover. The 5 μm hot-spots on Jupiter provide an example of such apparent time variation: not only are they variable in themselves, they are also affected by limb darkening.

True time variability is exemplified by phenomena dependent upon the amount of solar deposition (e.g., O_3 production on Earth), or condensation (e.g., H_2O on Earth). As specific examples, we note the differences observed by the Voyager IRIS in the C_2H_2 and C_2H_6 abundances and the reported appearance and disappearance of NH_3 on Saturn. Comets are well-known to exhibit time variability in their spectra. In addition, it might be expected that the intermittent volcanic plumes on Io will result in variations in the extended atmosphere of that body.

It is important to know the nature of the time variability (random or periodic) since these variations are directly related to specific physical phenomena such as photochemistry and atmospheric dynamics.

Vertical, Lateral and Temporal Distribution of Abundances

Measurement Requirements

Object	Venus/Mars	Jupiter/Saturn/Titan	Uranus/Neptune
Accuracy	10% (30%)	10% (30%)	10% (30%)
Precision	1% (2%)	1% (5%)	5% (20%)
Time Constant	1 min (30 min)	1 min (30 min)	1 min (60 min)
Sampling Interval	30 min (1 day)	30 min (1 day)	1 hr (1 mon)
Time Base		1 planet year (1 year)	
Resolution:			
Hor.		$\leq R/20$	
Vert.		$H/3$ (1H)	

NOTES:

1) Parentheses enclose "acceptable" values
2) R = planetary radius
3) H = phenomenon scale height

(10) Composition of Clouds and Aerosols

Knowledge of the composition of clouds and aerosols is fundamental to an understanding of planetary atmospheric chemistry, radiative heat budget, dynamics and climate, and the atmosphere-surface interaction.

The ubiquitous clouds of Venus, for example, play a particularly important role in the thermal balance of the planet. Although H_2SO_4 is believed to be the major cloud constituent on Venus there remains considerable uncertainty as to the composition of upper level hazes and the low level (mode 3) cloud layer. For Venus and the outer planets remote sensing is limited to the upper cloud levels; probes represent the only means of investigating their deep atmospheres.

The physical characteristics of the upper clouds of the outer planets are largely open to conjecture; data from the IRIS and NIMS instruments on the Voyager and Galileo spacecraft will do much to increase our understanding of the chemical nature of this complex cloud region in the atmosphere of Jupiter and provide guidance for future spectroscopic investigations of Saturn, Titan, Uranus and Neptune.

The water and CO_2 ice clouds on Mars play only a small role in the opacity of the atmosphere. However, dust arising from large scale dust storms is critical in establishing the thermal structure of the atmosphere from the surface to above 60 km. Injections of dust into the atmosphere act as drivers for global dynamical processes which can only be understood given knowledge of the physical properties and chemical composition of the dust. The dust particulates may also act as condensation nuclei providing a global transport mechanism for water on Mars. A limb-scanning low-to-medium resolution infrared spectrometer would be an effective means of identifying the chemical and mineral composition of the Martian dust.

Composition of Clouds and Aerosols

Measurement Requirements

Object	Venus	Mars	Outer Planets/Titan
Accuracy	5% (10%)	5% (10%)	5% (10%)
Precision	1% (2%)	2% (4%)	1% (2%)
Time Constant	1 day	1 day	30 min
Sampling Interval	1 day (1 wk)	1 day (1 wk)	30 min (1 hr)
Time Base	10 planet years (1 year)	1 planet year (1 year)	1 planet year (1 year)
Resolution:			
Hor.	≤R/20	≤ R/20	≤ R/20
Vert.	1 H	H/2 (1 H)	H/2

NOTES:

1) Parentheses enclose "acceptable" values
2) R = planetary radius
3) H = phenomenon scale height

(11) Radiative Properties of Clouds and Aerosols

The ability of the cloud and aerosol particles present in planetary atmospheres to scatter and absorb radiation has many important effects in regions of the spectrum from the ultraviolet to the infrared. Dark aerosols high in the stratosphere can absorb sufficient ultraviolet radiation to contribute to thermal inversions in the upper atmospheres of several outer planets and Titan. The albedo and single-scattering phase function of the aerosols in the visible determine the amount of sunlight absorbed by the planet, and at continuum wavelengths control the penetration of sunlight into the atmosphere. In the infrared, the opacity of the aerosols can control the amount of radiation escaping to space (as they do on Venus) and significantly affect the temperature structure of the atmosphere. The ability to invert spectra of the thermal emission of (especially) the outer planets can depend sensitively on a knowledge of the opacity of the clouds at the wavelengths of the measurements.

If sufficient information on the cloud microstructure (particle size, shape, and composition) and macrostructure (vertical and horizontal distribution) is known, it should be possible to compute the radiative opacity of the clouds at any wavelength. Cloud micro and macrostructure information is by far the most complete for Venus (see below), yet recent attempts to compute the thermal emission from Venus using cloud opacities evaluated in this way have exceeded the measured bolometric flux by some 30 percent. Apparently, even for the relatively well known clouds of Venus, significant aerosol thermal opacity remains to be included.

For the outer planets, present information on macrostructure is much less complete than for Venus, and microstructure is almost unknown. Thus the problems of determining the temperature profile, vertical cloud structure, and the single-scattering properties of the particles from radiation measurements are all interrelated. One approach is to use continuum observations of reflected sunlight at a variety of phase angles to determine the single-scattering phase function and albedo of the particles. Observations in nearby gaseous absorption bands can be interpreted using the single-scattering properties derived from the continuum observations to give the vertical distribution of the cloud opacity.

However, without some information on the size, shape and composition of the aerosols, it is difficult to predict reliably the properties of the aerosols at wavelengths far from a wavelength at which they have been measured. Thus cloud properties derived in the visible provide a somewhat uncertain guide to cloud opacity in the infrared. Direct measurements in the infrared at wavelengths up to a few microns are possible from outside the atmosphere but are complicated by the difficulty of finding continuum regions and the resulting dependence on cloud vertical location as well as opacity.

Infrared measurements of net radiative flux from an entry probe are an extremely valuable source of "ground truth" for measurements made from outside the atmosphere. Probe measurements of net flux in narrow infrared spectral intervals where gaseous opacity is small can be combined with probe measurements of the temperature profile to give immediately the thermal opacity of the clouds.

Ideally, one would like to know the single-scattering phase function and albedo and the extinction optical depth of the aerosols per unit volume at all wavelengths. Accuracies of 10-20 percent in the phase function and optical depth are desirable and achievable if the radiation measurements have an internal consistency of 1-2 percent even if their absolute level is only accurate to 10 percent. Accurate determinations of single scattering albedos require absolute calibrations good to a few percent.

Spatial resolution requirements are dictated by the cloud structure of the planet of interest. Similarly, the time scales of interest vary over a wide range with the cloud systems from days to weeks for small features on Jupiter to several months for belts and zones.

Measurement strategies call for photometry at a variety of wavelengths over a wide range of phase angles (best done from an orbiter). If the instrument could also measure polarization, the resulting microstructure information would be useful for guiding the extrapolation of cloud properties to longer wavelengths. Careful selection of passbands for an infrared photometer or the use of a low resolution spectrometer might allow relatively direct retrieval of infrared aerosol opacities if the temperature profile were independently known (as from an entry probe or by other techniques). In any case, simultaneous probe measurements of temperature structure and the net flux at infrared wavelengths where gaseous opacity is small give the required information directly at the probe site and provide an important reference for the orbiter measurements.

Radiative Properties of Clouds & Aerosols

Measurement Requirements

Object	All
Accuracy	10% (20%)
Precision	1% (2%)
Time Constant	~mins
Sampling Interval	~mins
Time Base	1 planetary year (weeks)
Resolution:	
Hor.	1 km (R/20)
Vert.	H/10 (H/3)

Notes:

1) Parentheses enclose "acceptable" values
2) R = Planetary radius
3) H = Phenomenon scale height

(12) Cloud Microstructure

The aerosols present in planetary atmospheres have an important effect on the radiation field, the dynamics, and the thermal balance of the atmosphere. Before an understanding of the formation, growth, and life cycle of the aerosols can be reached, basic information on the microstructure - the size distribution, shape, and composition of the cloud particles must be determined. Existing information on cloud microstructure is most complete for Venus where ground based measurements have been possible over all phase angles and recent extensive measurements have been made from an orbiter and from four entry probes by the Pioneer Venus mission. Ground-based polarization measurements as functions of phase angle and wavelength indicated the cloud particles to be spherical with a radius near 1 μm and a narrow size dispersion. The inferred value of the refractive index and the shape of the Venus spectrum near 2.5 μm provided strong evidence that the cloud particles are composed of concentrated sulfuric acid.

Direct measurements of the size distribution of cloud particles were made by the cloud particles size spectrometer (LCPS) from the Pioneer Venus probe. These measurements confirmed the prevalence of 1 μm radius particles in the Venus upper cloud and also indicated the presence of distinct middle and lower cloud layers with trimodal size distributions containing size modes both larger and smaller than the 1 μm radius mode. Polarization measurements from the orbiter continue to reveal many details of the distribution of the 1 μm particles and an upper haze of substantially smaller aerosols.

The cloud physics of the Venus cloud particles still remain to be worked out in detail. One reason is the uncertainty in the composition of the largestmode of cloud particles found in the middle and lower cloud layers. In fact, the lack of any instrument capable of determining the composition of cloud particles was a notable deficiency in the PV probe payload.

For the outer planets, the very small range of phase angles available from the Earth is an important obstacle which can only be overcome by space missions. Polarization observations at a range of phase angles and wavelengths from flybys (Pioneer) or orbiters (Galileo) should provide information very helpful for determining cloud microstructure. There is, however, an important additional complication for these planets which makes the analysis of polarization data more difficult than in the case of Venus. While scattering calculations can determine the single-scattering phase matrix from observations of the polarization of the multiple scattered light, Mie theory cannot be used to determine the size and refractive index of the particles from their single-scattering properties because the particles are not spherical. It appears that laboratory cloud chamber measurements will be necessary to connect composition and crystal size and shape with single-scattering phase matrices.

Nevertheless, short of direct entry probe measurements, analysis of polarization data, while complex, provides a potentially very useful source of cloud microphysical data. Analyses of the Pioneer observations have placed tight constraints on the sizes of the cloud particles on Titan and Saturn, and single-scattering properties of the cloud particles on Jupiter, Saturn and Titan are being determined. Similarly, laboratory data on the polarizing properties of ammonia crystal clouds are currently being collected.

Ideally, one would like to repeat the Pioneer Venus type mission to each of the outer planets. The instruments should include a mapping photopolarimeter having filters spanning a wide wavelength range on an orbiter to provide global coverage. The orbiter measurements should be complemented by direct measurements from a few entry probes. The probes should contain a cloud particle size spectrometer (the PV LCPS instrument was extremely useful). An important complement to this instrument is provided by a multi-angle nephelometer (possibly including also polarization measurements). A method of determining cloud particle composition is very much needed, as revealed by the PV experience. An optical spectrometer appears to be an important instrument to be developed for future missions. Otherwise, the PV and Galileo polarimeter, nephelometer, and cloud particle spectrometer provide a solid base for new missions.

Cloud Microstructure

Measurement Requirements

Object	All
Accuracy	10% (particle size & no. density)
Precision	1% (5%) (particle size & no. density)
Time Constant	~hrs.
Sampling Interval	~hrs.
Time Base	1 week
Resolution:	
Hor.	---
Vert.	H/10 (H/3)

Notes:

1) Parentheses enclose "acceptable" values
2) H = Phenomenon scale height

(13) Cloud Macrostructure

This phenomenon describes the large-scale physical structure of clouds, hazes and atmospheric dust. These properties of aerosols include:

- Cloud height - the altitude and pressure level of a cloud top as seen at the wavelength of observation.
- Aerosol scale-height - the vertical distribution of the aerosol particles relative to the atmospheric scale.
- Cloud thickness - physical vertical extent of an aerosol layer.
- Cloud amount - the fractional amount of cloud cover at a level in the atmosphere.

These bulk cloud properties are important to an understanding of atmospheric structure, planet energy budget and latent heat transfer. Knowledge of these cloud properties is also of considerable importance for remote sensing techniques in the retrieval of atmospheric temperature, species abundances, winds and surface properties, among others.

Infrared techniques have been used extensively in the remote sensing of cloud macrostructure. Cloud height, for example, has been determined from down-looking Earth orbiting radiometer observations by a number of investigators including McCleese and Wilson (1972) and Chahine (1974, 1977). In planetary investigations these techniques have been used to map the cloud height and scale-height on Venus using narrowband spectral data from the Pioneer Venus Orbiter Infrared Radiometer. Measurements of cloud height for Jupiter and Saturn have been made with the Voyager IRIS instrument, and on Mars the distribution of atmospheric dust was determined by visible and near infrared observations from the Viking landers and orbiters.

Cloud Macrostructure

Measurement Requirements

Object	Venus	Mars	Outer Planets
Accuracy	5% (10%)	5% (10%)	5% (10%)
Precision	1% (5%)	1% (5%)	1% (5%)
Time Constant	1 hr.	30 min.	30 min. (1 hr.)
Sampling Interval	1 hr.	30 min. (1 day)	30 min. (1 wk.)
Time Base	10 planet years (1 planet year)	10 planet years (1 planet year)	1 planet year (1 year)
Resolution			
Horiz.	R/20	R/200 (R/20)	R/20 (R/10)
Vert.	H/5 (H/2)	H/10 (H/2)	H/5 (H)

NOTES:

1) Parentheses enclose "acceptable" valves
2) R = Planetary radius
3) H = Phenomenon scale height

(14) Non-LTE Phenomena

The breakdown of Local Thermodynamic Equilibrium (LTE) can result from a variety of causes: in low density atmospheres where the time between collisions becomes comparable to the radiative lifetime; in upper atmospheres subject to UV and charged particle irradiation; meteor trails; etc. In deep atmospheres the most prevalent would be lightning discharges.

In the infrared, the OH airglow emissions have long been studied in the Earth's atmosphere both for atmospheric investigations and for solar-terrestrial relations and the connection between aurorae and solar flares is well-known. Airglow phenomena have been detected on Venus (Stewart, 1980) and Mars (Stewart, 1972). Lightning has been detected on Jupiter and it has been suggested (Bar-Nun, 1975) that it could contribute to the observed chemical disequilibrium of that planet.

Non-LTE phenomena are important because they can have a substantial effect on radiative transfer, especially in tenuous atmospheres but with an observable impact on the spectrum of a planet, and can dominate the chemistry of upper atmospheres.

Because of the enormous diversity of these phenomena it is not possible to generate a "Measurement Requirements" table as for the previous sections; the time scales run from microseconds to hours or days and the spatial scales from cm to global. However, each is readily incorporated into one or other of the previous groupings so no information loss is entailed.

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CHAPTER II

REVIEW OF EXISTING INFRARED INSTRUMENTS

Any strategy for instrument development must be based upon a thorough understanding of those instruments that have been successfully employed for previous planetary missions and of those that have been, or are being developed, for relevant Earth applications. In this chapter we provide an overview of the various measurement strategies which have been developed to date. Table II-1 lists recently flown instruments and the accuracies to which they have measured various phenomena. More detailed descriptions of selected instruments appear at the end of this chapter.

Flown infrared instruments fall into four broad categories: radiometers (broadband radiometrically calibrated instruments), low-resolution spectrometers ($\lambda/\Delta\lambda$ typically $10^2 - 10^3$), high-resolution spectrometers ($\lambda/\Delta\lambda \sim 10^5$), and gas correlation spectroradiometers (spectral discrimination $\lambda/\Delta\lambda \sim 10^6$).

Radiometers of the 2-channel bolometric type (to measure reflected solar flux and total emitted flux) and multi-channel (generally filter) type for cloud properties and temperature and composition sounding on certain planets have been flown. Nadir, limb, in situ probes, and solar occultation viewing have all been successfully used (the latter for Earth only). Temperature retrievals accurate to a few K have been achieved on Earth. Synoptic studies of cloud lateral extent and height have been made for Earth and Venus. Some inferences of cloud structure have been possible for Jupiter and Saturn using radiometry. Bolometric temperature and net flux measurements have been made for the surface or clouds of all planets out to Saturn; the achieved accuracy ranges from .5 K on Venus to 2.5 K on Saturn; the radiation budgets of planetshave been measured by multiple-channel radiometers to accuracies of ± 10%. Solar net flux deposition profiles have been published for Venus, although certain questions about probe measurements will require more experience to resolve.

Recently flown or proposed infrared radiometers are:

Earth Orbital Radiometers

High Resolution IR Radiation Sounder (HIRS) Nimbus 6 1975
Limb Radiance Inversion Radiometer (LRIR) Nimbus 6 1975
Visible - IR Spin Scan Radiometer (VISSR) GOES 1-5 1975-81
Limb IR Moniter of the Stratosphere (LIMS) Nimbus 7 1978
Stratospheric and Mesospheric Sounder (SAMS) Nimbus 7 1978
IR Radiometer (IRR) Solar Mesophere Explorer 1981
Halogen Occultation Experiment (HALOE) Spacelab 3 1983
Cryogenic Upper Atmosphere Limb Emission Radiometer (CULER) UARS 1986

Planetary Radiometers

IR Radiometer (IRR) Mariner 10 1973
2-Channel Imaging Radiometer (IRR) Pioneer 10/11 1973
2-Channel Radiometer Venera 9/10 1975

IR Thermal Mapper (IRTM) Viking 1976
Orbiter Infrared Radiometer (OIR) Pioneer Venus 1978

In Situ Planetary Probe Radiometers

Solar Flux Radiometer (LSFR) Pioneer Venus 1978
Thermal Net Flux Radiometer (LIR) Pioneer Venus 1978
Solar/Thermal Net Flux Radiometer (SNFR) Pioneer Venus 1978
Net Flux Radiometer (NFR) Galileo 1986

Factors limiting the performance of radiometers have included difficulties in calibration (generally of the reflected solar component channels and in the 50-100 μm regime), modeling of the solar-thermal overlap region, schemes for long-term cooling of detectors for outer planet radiometry, temperature inversion algorithm development (see Appendix C), development of far-infrared filters and difficulties with operation on in situ probes.

Low-resolution spectrometers and spectroradiometers have utilized narrow filters and gratings with multiple detectors and circular variable filters with a single detector. These instruments have been developed for Earth and Mars; in development are a cryogenic limb viewing spectrometer for Earth and a mapping low resolution spectrometer for Jupiter and its moons. Surface thermal properties and vertical profiles of atmospheric temperature accurate to a few K for the terrestrial planets can be achieved by careful wavelength selection and temperature retrieval algorithm construction if the atmospheric composition is known. Vertical profiles and horizontal distribution of minor atmospheric constituents (via limb sounding) with rms errors ~ 10% and cloud structure can be retrieved. Low-resolution in situ spectrometers have been flown on Soviet Venera probes for solar absorption studies of atmospheric composition. Characterization of the mean size of aerosol particles through the wavelength dependance of their scattering function is proposed for one such instrument now in fabrication. Detection and abundance of species produced in comets, and mean particle size and production rates of cometary dust tails seems within presently-developed capabilities.

The Venera 9 and 10 entry probes (1975) carried a low resolution circular variable filter (CVF) Spectrometer to profile atmospheric constituents. Two low resolution spectrometers are in development for 1986 missions: the Galileo orbiter near-IR mapping spectrometer (NIMS), an imaging spectrometer, and the cryogenic upper-atmosphere limb emission radiometer (CULER) proposed for UARS, which uses a 1% resolution CVF.

Factors limiting the performance of low-resolution infrared spectrometers include lack of sufficient knowledge of atmospheric opacity sources to permit accurate channel selection, uncertainty as to the applicability of techniques for including clouds and hazes in temperature retrievals for the giant planets, contributions of uncertainties in knowledge of line shapes and local thermodynamic non-equilibrium to temperature inversion schemes. Long-term detector cooling techniques. (80K for 1-12 μm detectors) are required, as well as studies of cryogenic mechanism operations and development of radiation sources and sampling proceedings for in situ spectrometers.

Medium/high-resolution spectrometers and spectroradiometers of both the grating type and the interferometric type have been utilized for survey and constituent-specific studies on Earth, Mars, Jupiter, and Saturn. Spectral resolutions of 2.4-5 cm^{-1} have been achieved in the 4-55 micron region with spaceborne Michelson interferometers using thermopile and thermistor bolometer detectors. Resolution of .01 cm^{-1} over the 2.5-15 micron spectral regime will be achieved by one solar occultation interferometer for studies of trace molecule abundances to concentration levels of as low as part in 10^{13} in the Earth's stratosphere. The variation of water vapor column abundance on Mars has been mapped with a grating instrument with 1 cm^{-1} resolution to concentrations of 10 ppm, with an accuracy of 5%. Instruments operating in both nadir-looking and solar occultation mode have been constructed. These instruments have demonstrated radiometric calibration to ± 1 K for Earth and ± 3 K for Jupiter.

The following medium/high resolution spectroradiometers have been flown or are in development: IR Interferometric Spectrometer (IRIS) flown on Nimbus 3 and 4, Mariner 9, Voyager 1 and 2; Mars Atmospheric Water Detector (MAWD) on the Viking Orbiter; Atmospheric Trace Molecules Occulation Spectrometer (ATMOS) on Spacelab 3; and Cryogenic limb-scanning Interferometer and Radiometer (CLIR).

Factors limiting the performance of high-resolution spectrometers include lack of high stability spacecraft pointing for solar occultation spectroscopy of outer planet atmospheres, lack of on-board processing of interferograms, extension of spectral range to include the near and far infrared, and development of imaging capability.

Gas Correlation Spectroradiometers are devices which achieve extremely high spectral discrimination, high selectivity and high throughput for measurement of species abundance and atmospheric temperature. The pressure modulator radiometer approach employs a cell of gas whose pressure is cycled about a mean value by a resonant piston. The incident atmospheric radiation passes through the cell on its way to a detector. The absorption spectrum of the gas matches line for line the emission (or absorption) spectrum of the same gas in the atmosphere so that as the pressure is cycled emission from that gas is modulated. Continuum emission and emission from other molecular species is largely unmodulated, hence radiation from a single molecular species may be selectively detected. Since the spectral interval is defined by narrow band pass all emission lines of the selected species within that interval contribute to the measured signal. Pressure modulation radiometry has been sucessfully used in Earth stratospheric and mesospheric temperature sounding (to $\sim$2.5K) and in determining vertical abundance profiles of minor constituents (to 10 - 30% at the ppb level) with half an atmospheric scale height vertical resolution. An instrument of this type with a CO_2 gas cell has been used on the Pioneer Venus orbiter for stratospheric and mesospheric temperature sounding to ±3K.

Gas correlation spectrometers have also been flown on NIMBUS 4 and 5 - the Selective Chopper Radiometer (SCR), NIMBUS 6 - the Pressure Modulator Radiometer (PMR), NIMBUS 7 - the Stratospheric and Mesospheric Sounder (SAMS) and on the Pioneer Venus Orbiter Infrared Radiometer (OIR), both in 1978.

Factors limiting the performance of correlation spectroradiometers include development of long hold-time coolable gas cells, high compression ratio long gas cells, availability of frequency translation devices, and radiometric calibration.

Ultra-high, sub-linewidth, resolution is being achieved by prototype ground-based laser heterodyne spectroscopy systems which may soon be available for spaceborne investigations of Earth and the other planets from Earth orbit. These techniques have discovered the existence of local non-equilibrium phenomena such as natural lasing on Mars, and have been used to determine directly winds by Doppler shift in certain instances. Development of space-qualified integrated acousto-optical filter banks, tunable local oscillators, and mixers for the 15-30 micron regime will permit greater utilization of this technique for research on selected planets.

BEST DOCUMENT AVAILABLE

Table II-1 Atmospheric Investigations by Recent and In-Development Spaceborne Infrared Instruments

PLANET	INSTRUMENT CLASS	ACRONYM(S)	DATE	MISSION(S)	PHENOMENA INVESTIGATED	RESOLUTION	ACCURACY
VENUS	2 Channel Radiometer	IRR	1974	Mariner 10	Cloud-Top Temperature		4 K
					Water Profile		30% at 10 ppm level
	2 Channel Radiometer	none	1975	Venera 9/10 Orbiter	Cloud Top Temperature		2 K
					Radiatiometric Albedo		3%
	Low Resolution Spectrometer	none	1975	Venera 9/10 Lander	Composition		
	10 Channel filter/Gas Correlation Imaging Radiometer	VORTEX, OIR	1978	Pioneer Venus Orbiter	Vertical Temperature Profiles		1 K
					Cloud Morphology	3 Km	
					Water Profile & Distribution		30% at 10 ppm level
					Radiometric Albedo		1%
					Thermal Balance		13%
	Solar Flux Radiometer	LSFR	1978	Pioneer Venus Probe	Vertical Profile of Solar Absorption		2%
					Vertical Structure of Clouds		
	Radiometer	LIR	1978	Pioneer Venus Probe	Vertical Profile of Net Thermal Flux		
					Vertical Profile of Water Abundance		
					Detection and Opacity of Cloud Layers		
	Net Flux Radiometer	SNFR	1978	Pioneer Venus Probes	Vertical Profile of Net Heating Rate		
EARTH (sample)	2 Channel Imaging Radiometer	VISSR	1975-81	GOES 1-5	Cloud Cover	9 km	
	17 Channel Radiometer	HIRS	1975	NIMBUS 6	Vertical Temperature Profiles		
					Water Profiles		
					Cloud Cover	25 Km	
	Filter Radiometer (limb scanning)	LRIR,LIMS,IRR	1975-78	NIMBUS 6&7, SME	Vertical Temperature Profile		1 K at 15 km, 2.5 K at 65 km
					Trace Constituent Abundance Profiles	1.4 x 16 km	10-40% at ppb level
	Filter/Gas Correlation Radiometer (limb scanning)	SAMS	1978	NIMBUS 7	Vertical Temperature Profile	.001 cm^{-1}	1-2 K at 15-80 km
					Vertical Distribution & Trace Constituent Abundance		20% at ppb level, 15-80 km
	High Resolution Spectroradiometer (solar occultation)	ATMOS	1983	Spacelab 3	Trace Constituent Abundance		20% at 1 in 10^{13} level
	Gas Correlation Radiometer (solar occultation)	HALOE	1984	ERBS,Spacelab 3	Halogen Abundance Profiles	2 Km	
	8 Channel Radiometer	ERBI		ERBS	Thermal Balance		
	High Resolution Spectroradiometer	CLIR	1984		Profiles of Trace Constituents	2 Km	
					Vertical Temperature Profiles		
MARS	Medium-High Resolution Spectrometer	IRIS	1971	Mariner 9	Composition	2.4 cm^{-1}	
					Surface Pressure		
					Vertical Temperature Profiles		
	12-Channel Imaging Radiometer	IRTM	1976	Viking Orbiter	Surface Temperature	8 km	
					Atmospheric Temperature		
	Medium High Resolution Spectrometer	MAWD	1976	Viking Orbiter	Distribution & Abundance of Water		5% at 10 ppm level
JUPITER	2 Channel Imaging Radiometer	IRR	1973	Pioneer 10/11	Thermal Balance		3%
					Helium/Hydrogen ratio		6%
					Atmospheric Temperature	655 x 2200 km	8%
					Cloud Morphology & Vertical Structure		
	Medium High Resolution Spectroradiometer	IRIS	1979	Voyager 1/2	Thermal Balance		5.1%
					Helium/Hydrogen ratio		4.1%
					Composition	4.3 cm^{-1}	
					Atmospheric Temperature		
					Cloud Morphology & Vertical Structure		
	Mapping Low Resolution Spectrometer	NIMS	1984	Galileo Orbiter	Species Distribution & Variation		
					Vertical Temperature Profile		
					Size of Aerosols		
	Net Flux Radiometer	NFR	1984	Galileo Probe	Vertical Flux Profile		
					Cloud Layering		
					Opacity Sources		
SATURN	2 Channel Imaging Radiometer	IRR	1978	Pioneer 11	Thermal Balance		3%
					Helium/Hydrogen ratio		>3%
					Atmospheric Temperature		8%
					Cloud Morphology & Vertical Structure		
	Medium-High Resolution Spectroradiometer	IRIS	1980-81	Voyager 1/2	Thermal Balance		
					Helium/Hydrogen ratio		
					Composition	4.3 cm^{-1} *	
					Atmospheric Temperature		
					Cloud Morphology & Vertical Structure		

DETAILED DESCRIPTIONS OF SELECTED IR INSTRUMENTS

HIRS

1. Class of Instrument:

Multi-Channel Imaging Radiometer

2. Name of Instrument:

High Resolution Infrared Radiation Sounder (HIRS)

3. Purpose:

Measure thermal emission from Earth in 17 spectral bands. Many channels are located in the 4.2 and 15μm CO_2 band to measure vertical temperature profiles; some are designed to derive water vapor profiles, others to identify clouds.

4. Vehicle and Date

Nimbus 6   6/12/75

5. Techniques:

HIRS is a 17 channel scanning radiometer. The spectral bands are defined by a combination of dichroic mirrors and individual filter elements. Some of the detectors are cooled to 120K by a radiative cooler.

The circular field of view, half amplitude separation of 1.24°, scans 36.9 degrees from nadir in both directions perpendicular to the ground track of spacecraft. Calibration is provided by observing two black bodies (270K and 300K) and deep space every 90 seconds.

6. Wavelength Region:

Channel Number	Central Wave-Number (cm^{-1})	Interval Between 50% Response (cm^{-1})	NER $10^{-7}W\ cm^{-2}sr^{-1}(cm^{-1})^{-1}$ ($T_{detector}$ = 118K)
1	668	2.8	3.00
2	679	13.7	.66
3	690	12.6	.45
4	702	15.9	.27
5	716	17.5	.52
6	733	17.6	.23
7	749	18.4	.27
8	900	34.6	.19
9	1224	63.4	.15
10	1496	87.6	.13
11	2190	20.6	.012

12	2212	22.5	.003
13	2242	21.6	.006
14	2275	35.2	.002
15	2357	23.0	.003
16	2692	296.9	.001
17	14443	892.2	--

7. Description

HIRS is a multichannel scanning radiometer designed specifically to meet the operational needs of the US weather service. The instrument operates with one channel in the visible part of the spectrum, the others being in the 3 to 15 μm wavelength range. A dichroic mirror separates the long wave channels (1 through 10) from the short wave channels (11 through 17). Two field stops are used. The long wave beam is chopped at 900 Hz. The short wave chopper is rigidly attached to the filter wheel and each short wave filter extends under several blades of the chopper to produce a chopping rate of 390 Hz.

8. Critical Performance Analysis:

The instrument functioned well. Data have been used at the Goddard Institute for Space Studies (GISS), New York and at NOAA/NESS, Suitland, Maryland

9. Future Potential and Development Required:

This instrument has been designed for a very specific purpose, meteorological sounding on Earth. Planetary application would require not only changes in optical filters, but also adaptations to the orbital speed of the spacecraft.

10. Literature References:

Chen, Y.M., Wolf, H.M., Smith, W.L.: Vertical resolution of temperature profiles from HIRS. NOAA Technical Report 67, NESS, Jan 74.

Smith, W.L., Wolf, H.M., Abel, P.G., Hayden, C.M., Chalfont, M., and Grody, N.: Nimbus 5 sounder data processing system Part 1. NOAA Technical Memorandum NESS 57, June 1974.

The Nimbus 6 User's Guide, John E. Sissala Editor, GSFC, Feb. 1975.

LRIR, LIMS, IRR

1. Class of Instrument:

   Limb scanning radiometer

2. Name of Instrument:

   Limb Radiance Inversion Radiometer (LRIR)
   Limb Infrared Monitor of the Stratosphere (LIMS)
   Solar Mesosphere Explorer Infrared Radiometer (IRR)

3. Purpose

   Sound Earth's stratosphere and mesosphere, for temperature and trace gas concentrations, and derive "geostrophic" winds, with high vertical resolution ($\leq$ 1/2 scale ht., ~4 km).

4. Vehicles and Dates:

   LRIR, Nimbus 6, June 1975
   LIMS, Nimbus 7, October 1978
   IRR, SME, Scheduled September 1981

5. Techniques:

   Infrared limb scanning measurement of IR limb emission in 3 or more spectrally broad channels (50-200 cm^{-1}) with vertically thin FOVs, as a function of relative position on scans across the planetary limb.

   This is followed by inference of temperature as a function of pressure, and then trace gas concentration as a function of pressure.

6. Wavelength Regions:

   LRIR, 8.5-24.3 μm
   LIMS, 6.2-16.8 μm
   IRR, 6.3-17.1 μm (Spec.)

7. Descriptions:

   LRIR:

   4 channel filter radiometer, HgCdTe detectors held at 63 K by 2 stage (CH_4-NH_3) solid cryogen cooler with 7 month life; scan rate 1°/sec, by scanning mirror. 15 cm off-axis folded telescope. Samples every 88 ms, 4 kbps data rate.

Channel	Purpose	Band Pass 50% pt. (cm^{-1})	FOV (km)		NEN (wm^{-2} sr^{-1})
			Vertical	Horizontal	
1	CO_2(T,p)	649-672	1.4	14	2.3-10^{-3}
2	CO_2(T,p)	592-700	1.4	14	4.0-10^{-3}
3	O_3	984-1169	1.4	14	11.-10^{-3}
4	H_2O	412-446	1.7	17	8.-10^{-3}

LIMS:

6 channel filter radiometer. As LRIR, except scan rate .25°/sec, samples every 22 ms.

Channel	Purpose	Band Pass 50% pt. (cm^{-1})	FOV (km)		NEN (wm^{-2} sr^{-1})
			Vertical	Horizontal	
1	NO_2	1580-1613	2.8	22.4	0.6-10^{-3}
2	H_2O	1396-1527	2.8	22.4	2.1-10^{-3}
3	O_3	947-1103	1.4	14	3.5-10^{-3}
4	HNO_3	859-900	1.4	14	1.5-10^{-3}
5	CO_2(T,p)	595-739	1.4	14	5-10^{-3}
6	CO_2(T,p)	645-673	1.4	14	1.3-10^{-3}

IRR:

4 channel filter radiometer. HgCdTe detectors at 105-120 K by passive cooling with Winston Horn. Scan rate 30°/sec, by rotating spacecraft. 20 cm off-axis folded telescope. Samples 2.5 ms, on limb, 128 bps data rate.

Channel	Purpose	Band Pass 50% pt. (cm^{-1})	FOV (km)		NEN (wm^{-2} sr^{-1})
			Vertical	Horizontal	
1	O_3	960-1155	3.6	36	3-10^{-3}
2	CO_2(T,p)	585-705	3.6	36	9-10^{-3}
3	CO_2(T,p)	635-680	3.6	36	6-10^{-3}
4	H_2O	1380-1585	3.6	36	2-10^{-3}

8. Critical Performance Analysis:

LRIR performed nominally, although cryogen life less than 1 year expected.

LRIR results:

Temperature--systematic error, $\leq 1^\circ$ of rockets
random error, 1°-15 km, 2.5°-65 km

O_3--systematic error, < 0.1 ppmV of rockets, z>30 km
$\sim$1 ppmV < rockets, 15 <z< 30 km
random error, 0.3 ppmV, 15-65 km.

High resolution achieved.

LIMS performed as expected. Same cryogenic cooler used.

Results--now being established.

T, O_3--should be about same as LRIR.

H_2O--systematic 20%, random 10-30%

HNO_3--systematic 15%, random 40%.

NO_2--systematic 30%, random 10-20%.

Determination of HNO_3 and NO_2 are first measurements of constituents in ppb range from space.

9. Future Potential and Development Required:

Future application to planetary exploration hinges on cooling the detectors and, for the outermost planets, perhaps cooling the telescope and optics.

Most attractive mode, from power and weight point of view, would be passive cooling, as now being employed on SME IRR.

Applications would require attention to,

1. Appropriate bands to use for temperature determination.

2. Appropriate bands to use for constituent determination.

3. NEI needed, and thus optics, detector D*, scan rate, etc.

4. Possible mechanization.

VISSR

1. Class of Instrument:

   Scanning Radiometer

2. Name of Instrument:

   Visible-Infrared Spin Scan Radiimeter (VISSR)

3. Purpose:

   Provide visible and infrared images of weather patterns on the Earth from geosynchronous altitude.

4. Vehicles and Dates:

   GOES 1 (1975), 2 (1977), 3 (1978), Scheduled D (1980), E (1981)

5. Technique:

   Full and partial pictures are obtained of the Earth's disc in an infrared (10.5-12.5 μm) and a visible channel (0.55-0.75 μm). Scanning in the E-W direction is accomplished by the satellite spinning motion. The latitudinal scan is accomplished by sequentially tilting the scanning mirror at the completion of each spin.

6. Wavelength Region:

   2 channels, visible (0.55-0.75 μm)
   infrared (10.5-12.5 μm)

7. Description:

   Both channels use a common optics system. Incoming radiation is received by an elliptically-shaped scan mirror and collected by a Ritchey-Chretien optical system. The scan mirror is set at a nominal angle of 45° to the VISSR optical axis, which is aligned parallel to the spin axis of the spacecraft.

   During each scan, eight visible detectors sweep the Earth, with a ground resolution of 0.9 km at zero nadir angle. A mercury cadmium telluride detector senses the IR portion of the spectrum with ground resolution of 9 km at zero nadir angle. The IR detector measures radiance temperatures in the range 180-315 K, with sensitivity 0.4-1.4 K.

8. Critical Performance Analysis:

The VISSR instruments on earlier versions have worked very well. They have provided day and night observations of cloud cover and Earth/cloud radiance temperature measurements. There has been some research use; a larger use has been for weather forecasting and pictures on TV.

9. Future potential and Development Required:

The VISSR Atmospheric Sounder (VAS) is under development as an atmospheric sounder from geosynchronous altitude. This provides a technique for observing shorter period phenomena (with vertical scales ~ H) which might be missed by an orbiter. Detector cooling could be a problem area. Additional modifications for planetary investigations should be relatively straightforward.

CULER

1. Class of Instrument:

   Limb viewing radiometer and spectrometer

2. Name of Instrument:

   Cryogenic Upper-atmosphere Limb Emission Radiometer (CULER)

3. Purpose:

   The objective of the CULER investigation is to study a number of selected questions in several areas of upper atmosphere science through analysis of global data sets extending from 20 to 140 km.

4. Vehicle:

   Accepted for definition phase for the Upper Atmosphere Research Satellite (UARS)--1984

5. Technique:

   The CULER will measure infrared emissions from the Earth's limb to take advantage of the inherent high resolution, enhanced sensitivity due to large absorber path length, and low background which characterize limb scanning.

6. Wavelength Region:

   Radiometer: 24 channels from 370-7000 cm^{-1}, Circular Variable Filter (CVF) spectrometer with 1% resolution between 650-5000 cm^{-1}

7. Description:

   The CULER instrument has a cryogenic telescope of 15 cm diameter with a limb scanning mirror feeding a 24 channel radiometer and a circular variable filter spectrometer. The spectral selectivity in multiple bands is achieved with a combination of grating spectrometer and interference filters. The 25 separate extrinsic silicon detectors are mounted in intimate contact with the cryogen tank so that they assume the 10 K temperature of the solid hydrogen cryogen. The spectrometers are cooled by the hydrogen to ~25 K and the remaining optics to ~50 K. A supply of 90 kg of solid H_2 is able to keep the entire instrument cold for two years of operation. The expected noise equivalent radiance (NER) values for all the spectral channels are less than 1×10^{-11} W cm^{-2} sr^{-1}. Dimensions are: length, 2.84 m and diameter, 1.48 m. The launch mass is estimated to be 530 kg decreasing by 90 kg during a 2 year mission. Power requirements are 30 W average and 45 W peak. Data bit rate is 20 kbps.

8. Future Potential and Development Required:

The very high requirements for telescope off-axis rejection and the verification of long term operation of a cryogenic scan mirror mechanism are areas which will require some development. No untried technologies are included in the design.

NIMS

1. Class of Instrument:

Low resolution imaging spectrometer

2. Name of Instrument:

Near Infrared Mapping Spectrometer (NIMS)
Comet Infrared Mapping Spectrometer (CIMS)

3. Purpose

NIMS: Study Jupiter's atmospheric composition, cloud structure, and thermal balance.
Map compositional units on Jovian satellites.

CIMS: Map near-nucleus coma species for Halley and Temple 2. Map compositional units on Temple 2.

4. Vehicles and Dates:

NIMS: Galileo Orbiter (1986)
CIMS: Proposed for International Comet Mission

5. Technique (NIMS):

High angular resolution images (0.2 mrad x 0.5 mrad) are made with 0.6% wavelength resolution throughout the wavelength region. The spectral resolution may not be sufficient for an unambiguous identification of new minor Jovian atmospheric constituents; however the observations at high spatial resolution of well known absorption bands in the Jovian spectrum can successfully be used for a determination of atmospheric parameters (temperature profiles and density distributions) as a function of their location on the Jovian disk. Moveover, the observation of the Jovian flux at selected wavelengths, inside and outside the spectral bands of well known absorbers (methane, ammonia, and phosphine) can be used to study time-dependant processes (circulation, photodissociation, and chemical reactions).

6. Wavelength Region:

0.7 - 5.2 μm

7. Description (NIMS):

Angular Resolution:	0.2 mrad x 0.5 mrad
Angular Field:	10 mrad (20 pixels) x 0.5 mrad (1 pixel).
Spectral Range:	0.7 - 5.2 μm
Spectral Resolution:	0.6%; $\Delta\lambda = 0.025\ \mu m$ ($\lambda > 1\ \mu m$); $0.013 \mu m$($\lambda < 1\ \mu m$).
Spectral Scan Time:	4 1/3 seconds (20 pixels, 204 wavelengths).

Telescope:	23 cm (9") diameter f/3.5 Ritchey - Chretien, Wobbling secondary for spatial scan, 800 mm equivalent focal length.
Etendue (A):	1.1 x 10^{-4} cm^2 sterad.
Spectrometer:	40 lines/mm plane-grating spectrometer, F/3.5 Dahl-Kirkham collimator f = 400mm, F/1.75 wide-angle flat-field camera f = 200mm.
Detectors:	InSb (15), Si(2), discrete elements, quantum efficiencies 70-80%, Noise Equivanent Power = 10^{-14} Watts, D* = $3x10^{13}$ cm $\sqrt{Hz}$ $Watt^{-1}$.
Cooler:	Passive radiative cooler, 80°K operation.
Noise Equiv. Radiance:	1.2 x 10^{-9} W cm^{-2} $sterad^{-1}$ per spectral resolution element (0.025 μm) at 3 μm.
Mechanisms:	Torque motor drives for spatial and wavelength scan, Tuning fork chopper, Covers for telescope and radiative cooler.
Electronics:	17 channel signal chain, Microprocessor control (RCA 1802), Timing synchronous with imaging subsystem.
Protective Devices:	Covers for dust and contamination protection, Heaters for contamination control, Instrument purging through launch.
Mass:	18.0 kg.
Power:	8 W (average) 12 W (peak).
External Dimensions:	82.6 x 36.8 x 39.1 cm (optics), 20.3 x 25.4 x 12.7 cm (electronics).
Data Rate:	11.52 kbps
Mounting:	Scan platform, bore sighted with imaging subsystems.
On Board Calibration:	Diffuse reflectance target and extended blackbody (spacecraft supplied).

IRIS

1. Class of Instrument:

Low Resolution Spectrometer (Fourier Transform)

2. Name of Instrument:

Infrared Interferometric Spectrometer (IRIS)

3. Purpose:

Measure thermal emission from planets to derive atmospheric composition, vertical temperature profiles, the wind field, surface pressure and topography, energy balance, cloud composition and density.

4. Vehicle and Date

Nimbus 3	4/14/1969
Nimbus 4	4/8/1970
Mariner 9	5/8/1971
Voyager 1	9/5/1977
Voyager 2	8/20/1977

5. Technique:

IRIS is a Michelson interferometer using KBr and CsI beam splitters with compensating plates, one moving and one stationary flat mirror, linear motion phase locked to a stable clock frequency, and a reference interferometer with a neon source for the generation of sampling commands and phase locking.

6. Wavelength Region:

Table 1

Nimbus 3	400-2000 cm^{-1} (5-25 μm)
Nimbus 4	400-2000 cm^{-1} (5-25 μm)
Mariner 9	200-2000 cm^{-1} (5-50 μm)
Voyager 1	180-2500 cm^{-1} (4-55 μm)
Voyager 2	180-2500 cm^{-1} (4-55 μm)

7. Description

The spectral resolution in the apodized mode of data reduction has been a few cm^{-1} as indicated in Table II-2.

Table II-2

Spacecraft	Resolution (cm^{-1})	NESR ($W\ cm^{-2} sr^{-1}/cm^{-1}$)	Operating Temp. $^{\circ}K$	Detector
Nimbus 3	5	5×10^{-8}	250	Therm Bol
Nimbus 4	2.8	7×10^{-8}	250	Therm Bol
Mariner 9	2.4	4×10^{-8}	250	Therm Bol
Voyager 1	4.3	5×10^{-9}	200	Thermopile
Voyager 2	4.3	5×10^{-9}	200	Thermopile

The Nimbus and Mariner interferometers operate without a telescope; the Voyager instruments use Cassegrain telescopes with 50 cm diameter primary mirrors. All IRIS have achieved absolute radiometric calibration.

8. Critical Performance Analysis:

All IRIS instruments on all 5 space missions have worked satisfactorily and have achieved their scientific objectives. IRIS on Nimbus 3 failed after more than three months in Earth orbit by failure of the thermistor bolometer detector. On Nimbus 4 IRIS functioned for several years although data were recorded regularly for only one year. On Mariner 9 IRIS operated flawlessly during the spacecaft life time. On the Voyagers both instruments have experienced minor misalignment and require occasional warming from the operating temperature of 200K to approximately 270K to maintain full flexibility of a silicone rubber compound used in the drive motor and beam splitter mount.

9. Future Potential and Development Required

Future developments are desirable in several areas: first, extension of spectral range towards the near and far infrared, second, reduction in noise equivalent spectral radiance and third, increase in spectral resolution.

Extension of spectral radiance towards the near and far infrared is desirable to capitalize on information from reflected solar radiation and far infrared emission. The latter is particularly desirable for investigations of low temperature bodies found in the outer solar system. Basic technology exists but needs to be demonstrated in specific design.

The major advance in infrared spectroscopy from space missions will come from the use of cryogenic detectors. Cryogenic technology needs to be made available for long duration missions before major advances in IRIS performance can be realized. With cryogenic detectors a Michelson type interferometer with a wide spectral range and a resolution in the order of a small fraction of a wavenumber becomes feasible. Such an instrument would be invaluable for planetary space research.

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CLIR

1. Class of Instrument:

   Limb viewing interferometer and radiometer

2. Name of Instrument:

   Cryogenic Limb-scanning Interferometer and Radiometer (CLIR)

3. Purpose:

   CLIR is a multi-user instrument designed for remote sensing of the Earth's atmosphere, over a limb tangent range of 20-140 km, in order to obtain observations with which to answer the significant questions about the chemistry, physics and motions of this atmospheric region.

4. Vehicle:

   Proposed for Space Shuttle--1984

5. Technique:

   The CLIR instrumentation consists of a Michelson-type interferometer spectrometer and a multichannel radiometer. These cryogenic instruments share adjacent narrow fields of view in order to view emissions from the Earth's limb. The basic mode of operation is limb scanning with an altitude resolution of 2 km at the limb from Shuttle orbit.

6. Wavelength Region:

   Interferometer: 400-4000 cm^{-1}
   Radiometer: 25 channels from 400-8000 cm^{-1}

7. Description:

   CLIR will employ a baffled off-axis spherical telescope of low scatter and high off-axis rejection. The telescope has an aperture of 25 cm diameter with a 1 mrad field of view. Baffles will be cooled to 115 K and optics will be maintained at 30 K by a single-stage supercritical helium cryogen system. The interferometer will have a 5 cm diameter aperture with a commandable resolution of from 0.1 cm^{-1} (10 s scan time) to 1 cm^{-1} (1 s scan time). The radiometer will have 25 channels defined by the dispersion from an Ebert grating spectrometer and subsequent imaging onto focal plane detector arrays. The radiometer focal plane detectors and the interferometer detector will be at approximately 10 K, the temperature of the cryogen. Detectors will be extrinsic silicon detectors. With bismuth-doped silicon the noise equivalent spectral radiance (NESR) for the interferometer at .1 cm^{-1} resolution and a 10 s integration time is $\sim 2 \times 10^{-12}$ W cm^{-2} sr^{-1} (cm^{-1})$^{-1}$ at 400 cm^{-1}. The noise equivalent radiance (NER) values for the radiometer channels are all less than 2×10^{-11} W cm^{-2} sr^{-1}. Dimensions are 80 cm diameter and 300 cm length. Mass with cryogen for a 30 day mission is 480 kg (70 kg of which is cryogen). Power requirements are 95 W average and 170 W peak. Expected bit rate is 500 kbps.

8. Future Potential and Development Required:

The radiometer focal plane detector arrays are modular so that they may be replaced with arrays which incorporate improved detectors and/or different spectral channels. Aspects of CLIR which will require some development are the proving of the very high tolerance for off-axis rejection (10^{-10} at 1 deg) and testing of the 30 K interferometer, although no untried technology is incorporated in the CLIR design.

SAMS

1. Class:

Multichannel Gas Correlation Radiometer

2. Name:

Stratospheric and Mesospheric Sounder (SAMS)

3. Purpose:

Stratospheric mixing ratios of CO, NO, N_2O, CH_4, H_2O. Stratospheric temperatures. Mesospheric CO, NO, H_2O. Mesospheric temperature. Attitude measurement independent of spacecraft attitude control system.

4. Vehicle & Date:

Nimbus 7, September 1978

5. Technique:

Broad band and pressure modulation radiometry in a limb sounding configuration.

6. Wavelength Regions:

Several emission bands in the infrared, namely: 2.7 μm H_2O, 4.3 μm CO_2, 4.7 μm CO, 5.6 μm NO, 7.8 μm N_2O, 7.8 μm CH_4, 15 μm CO_2, 25 μm -100 μm H_2O.

7. Description:

Radiation from a limb path is collected by a telescope of area 177 cm^2 pointed perpendicularly to the spacecraft motion. At the secondary focus of the telescope is a multifaceted field mirror which directs the radiation into 3 optical chains, each with a field of view at the tangent point 100 km horizontally and 10 km vertically. The fields are separated vertically, the lowest being 30 km below the middle which itself is 10 km below the highest. All three may be scanned simultaneously both vertically (limb scan) and horizontally (azimuth scan). A shallow (2.5% depth of modulation) tuning fork black chopper placed before the field mirror imparts broad band amplitude modulation at 250 Hz to radiation from all three fields. In-flight calibration is performed by a two point calibration sequence involving measurement of the radiation from space and from a 295 K black body placed at the telescope primary focus.

The three optical chains contain pressure modulated cells, which impart wavelength dependent amplitude modulation in the 25-40 Hz range, filters and beam splitters which define the optical bandpasses, and detectors. Seven pmc's are used containing H_2O vapor, CO, NO, CO_2 (2), N_2O and CH_4. Five detectors are used - TGS at 30°C, PbS at 0°C and InSb cooled to 160 K by a radiative cooler, having NEP's of approximately 2×10^{-10}, 8×10^{-13}, and 8×10^{-13} (at 170 K) Watt/$\sqrt{Hz}$ respectively.

Signal processing consists of preamplification filtering synchronous detection and integration by a 12 bit dual slope integrating A/D converter. A controller allows the fields of view to be scanned and the mean pressure in the pmc's to be changed during flight on ground command.

8. Performance Analysis:

Signal to noise performance of the SAMS instrument in operation is listed in Table II-3.

Table II-3

SAMS Signal to Noise Performance

	Spectral Region	S/N (290K black body)
A1 pmr (CO_2)	15 μm	48
A1 wideband		315
A234 pmr (CO_2/NO)	4-5 μm	5.9
A234 wideband		290
B2 pmr (H_2O)	25-100 μm	26
B2 wideband		73
C1 pmr	15 μm	98
C1 wideband		202
C23 pmr (CH_4/N_2O)	7.7 μm	33
C23 wideband		50

Each channel in Table II-3 has commandable mean cell pressures by means of molecular sieves. Channels for which two gases are given (e.g. A234 CO_2/NO) have two pressure modulated cells in series in the optical chain.

Table II-4 lists the integration time required for a noise equivalent emissivity of 0.03.

Table II-4.

Integration Time for SAMS to Achieve Noise Equivalent Emissivity of 0.03

Observed Constituent	Spectral Region	Time (sec)
CO_2	4.3 μm	10000
NO	5.3 μm	400
N_2O/CH_4	7.7 μm	10
CO_2*	15. μm	4
H_2O	25-100 μm	5

*NEE = 0.01: Temperature sounding channel, 1K resolution

Channel A234 (4.3 μm) failed to meet performance goals due to failure of the radiant cooler to reach temperatures below 165K (design goal 130 - 160K). Development of closed-cycle coolers is currently underway by the investigators for further use of the SAMS instrument.

9. Future Potential and Development Required:

Cooled detectors may be employed thus improving performance by up to two orders of magnitude. Comparative figures for noise equivalent power (NEP) for currently available detectors are listed in Table II-5. The detectors operated near 70K, below the range accessible using radiant coolers, require a long-life closed-cycle cooler.

The eventual use of photon noise limited detectors and the measurement of very low radiant energy sources will necessitate the development of cooled pressure modulated cells. The implementation (where appropriate) of cryogenically controlled molecular sieves to freeze out the gas from the cell might be used in a diagnostic procedure to check the optical properties of the empty pressure modulated cell in flight.

The techniques of gas correlation, as applied in the pressure modulation channels of the SAMS instrument, has potential for development as a passive wind sensor. Operating as a detector of wind induced Doppler shifts, such a pressure modulation radiometer may be capable of directly measuring wind with an accuracy of a few m/s in atmospheric regions in which Doppler line broadening is dominant.

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Table II-5

Pressure Modulation Channel Performance With Cooled Detectors

Channels	Improved SAMS Detector			SAMS Detector		
	Type	Temp (K)	*NEP W $Hz^{-1/2}$	Type	Temp (K)	*NEP W $Hz^{-1/2}$
15 μm CO_2	MCT	70	2.10^{-12}	TGS	290	$0.9.10^{-10}$
25-100 μm H_2O	TGS	290	$0.0.10^{-10}$	TGS	290	$0.9.10^{-10}$
7.7 μm, N_2O, CH_4	MCT	70	5.10^{-13}	TGS	290	$0.9.10^{-10}$
4-5.5 μm CO_2, NO, $CO_2(\nu_3)$	InSb	70	2.10^{-13}	InSb	160	10^{-11}
2.7 μm H_2O	PbS	190	2.10^{-13}	PbS	260	6.10^{-13}

*NEP for 0.01 cm^2 area at appropriate frequency

HALOE

1. Class of Instrument:

   Gas filter correlation radiometer and broadband spectral filter radiometer

2. Name of Instrument:

   Halogen Occultation Experiment (HALOE)

3. Purpose:

   To make solar occultation measurements of upper atmospheric vertical concentration profiles of key ClO_x, NO_x and HO_x constituents. To study trace gas sources and sinks and upper atmospheric transport.

4. Vehicle:

   Engineering model for Spacelab 3--1982
   Flight model for AEM-D/ERBS--1983
   Proposed for the Upper Atmosphere Research Satellite (UARS)--1986

5. Technique:

   The HALOE instrument will measure Earth limb absorption with the Sun as a source using four gas filter correlation channels and five broadband filter radiometer channels. The instrument has internal azimuth and elevation scan capabilities.

6. Wavelength:

   9 channels from 860-4150 cm^{-1}

7. Description:

   A 16 cm diameter Cassegrain telescope images the Sun to a field stop defining a vertical instantaneous field of view of 2 arc minutes (2 km at the horizon from 600 km altitude). A reflecting chopper diverts energy to the five filter radiometer channels designated for H_2O, CF_2Cl_2, O_3, HNO_3 and CO_2. Dichroics split the chopped radiation into four gas detection modules. The present correlation gases are HCl, HF, NO and CH_4. Dual detectors are used in each of the four gas detection modules. Because of the large signal levels provided by the solar source all detectors are uncooled. The expected noise equivalent modulation (NEM) is approximately 2×10^{-5}. Separate optics are provided for the pointing/tracking system. Nominal mass and dimensions are: mass, 75 kg; optics unit, 28 x 45 x 75 cm and electronics 22 x 22 x 20 cm. Power consumption is 60 W during normal operation with a peak of 75 W. Data rate is 4296 bps.

8. Future Potential and Development Required:

The construction of the HALOE instrumentation allows interchange of the gas correlation cells and spectral filters so that other gases may be investigated. Some feasible gases of interest are OCS, $CFCl_3$, N_2O, NO_2, CO and possibly COF_2 and CCl_4. Some development will be required to prove the reliability of the gas correlation cells for long term missions.

CHAPTER III: CRITICAL COMPARISON OF MEASUREMENT TECHNIQUES

In this chapter we investigate the performance of infrared measurement techniques as the basis for detailed intercomparisons of instrument capabilities. Measurement techniques having similar spectral resolution or sharing a common technology have been grouped in broad categories. While no attempt was made to evaluate in detail the performance of all observational techniques in addressing all phenomena, representative experiments were either modeled numerically or considered by extrapolation from reported performance of an instrument. The categories are meant to include all known infrared methods for implementing an observational technique.

We investigate the properties of the following instruments:

(1) Narrow-Band Filter Radiometer
(2) Imaging Infrared Spectrophotometer
(3) Medium-to-High Resolution imaging Spectroradiometer
(4) High Resolution Infrared Spectrometer
(5) Correlation Spectroradiometer
(6) Heterodyne Spectrometer
(7) Entry Probe Spectrometer
(8) Polarimeter
(9) Net Flux Radiometer
(10) Two-Channel, Wide-Field Bolometric Radiometer
(11) Two-Channel, Narrow-Angle Bolometric Radiometer

Measurement Technique Evaluations: In each instrument category the approach used to evaluate the capability of an instrument was:

- Observation strategies were selected (e.g., orbital platforms, flyby and probe spacecraft, and near-Earth orbiting telescope facilities) from which experiments might be performed.

- In most cases, numerical models of instrument performance were constructed for representative experiments.

- One or more specific instrument designs were evaluated within each instrument category to ensure that conclusions reached about the category as a whole were representative. Unique capabilities of a particular approach were emphasized.

The utility of a measurement technique was initially established by comparison of the expected instrument performance to the measurement requirements of Chapter I. The required detector performance, measurement integration time, telescope size, instrument mass, etc., was also considered.

Finally, the need for instrument development in each measurement category was reviewed, including the heritage of existing hardware and the status of current or planned instrument development activities. Hardware in critical need of development has been identified and specific areas of effort recommended order to ensure its readiness for future missions.

III - I. NARROW-BAND FILTER RADIOMETER

This class of instrument uses a number of approaches for obtaining spectral selectivity; the commonality arises from the pass-band employed $(\Delta\lambda/\lambda \geq 1\%)$. In its most simple form a radiometer may consist of collector optics, spectral interval selection element, and a detector. For accurate radiometric measurements at least two calibration targets (either internal or, preferably, external to the instrument) of known emissivity and differing temperature are needed.

Applications of radiometers to atmospheric phenomena have increased in number as calibration techniques, filters and detectors have improved. Radiometers have evolved to measure atmospheric temperature structure and molecular species amounts into the parts-per-billion range. Most recently, with the introduction of the techniques of vertical limb scanning, narrow band infrared radiometers have been used to determine the vertical distribution of many gaseous components of atmospheres.

These instruments are limited to non-survey investigations of atmospheres since the detailed spectral information within the instrument pass-band is lost. The requirement for prior knowledge of the atmospheric constituents which may contribute significantly to the character of the spectral interval of interest may exclude some applications of the method.

Instrument Specifications

The measurement strategy of limb sounding (the instrument in orbit viewing tangentally through the limb of the atmosphere) has been chosen to review the performance of infrared radiometers. Substantial experience with nadir looking radiometers exists, and much of what is presentedhere describing limb sounding capabilities also applies to nadir sounding. The limb sounding strategy provides maximum vertical resolution for most experiments, and gives the radiometer maximum sensitivity to low abundance species at the cost of limited penetration into the deep atmospheric layers.

The specifications given below were used to model the performance of the hypothetical instrument presented in the examples which follow.

Collector: 16 cm diameter (Venus and Mars sounder)
23 cm diameter (Jupiter and Saturn sounder)

Detector Figure of Merit: $D^* = 10^{14}$ cm $Hz^{1/2}$ W^{-1} (Venus and Mars)

$D^* = 10^{13}$ cm $Hz^{1/2}$ W^{-1} (Jupiter and Saturn)

Spectral Pass-Band: $\frac{\Delta\lambda}{\lambda} \geq 0.01$

Field-of-View (limb): Vertical = H/2*
Horizontal = 5H

Thermal Requirements: instrument, detector and collector cooled

*H = scale height of atmosphere

Application Analyses

(1) Venus temperature sounding and water-vapor abundance profiles.

We have used the example of temperature sounding of Venus as an illustration of a highly successful application of radiometry. Results from the Pioneer Venus Orbiter Infrared Radiometer have already demonstrated the capability of sounding vertical temperature structure using both nadir and limb observation strategies. This instrument also obtained results pertaining to the column abundance of water-vapor above the clouds of Venus. Modeling of our hypothetical instrument, which is more complex by virtue of use of cold detectors and optics, shows excellent capabilities in sounding temperature at 15 μm in the $\sim$50 mb to 10^{-4} mb pressure height interval, with a vertical resolution of 4 km. Estimates of measurement times for these limb observations are $t \ll 0.1$ sec. for noise-equivalent temperatures (NET) < 0.1K.

Vertical profiles of water-vapor abundance may be obtained in the 20 μm part of the rotation band over the $\sim$50 mb to 10^{-2} mb pressure height interval. Measurement times are $t \ll 0.1$ sec for water-vapor abundance accuracies of 10%. The vertical resolution in the profiles is 3-4 km. The measurement of species concentrations by radiometry is, of course, dependent upon knowledge of the vertical temperature profile.

(2) Mars water-vapor abundance profiles.

Using the 20 μm rotation band of water-vapor a radiometer viewing the limb of Mars can determine the vertical abundance profile in the 5 mb to 10^{-4} mb pressure height interval with a vertical resolution of 5-10 km. The measurement accuracy is estimated to be near 20% for measurement times of $t < 1$ sec., assuming that the atmospheric vertical temperature profile is also determined. The dust loading of the atmosphere is of critical importance in radiometric sounding of Mars. Dust is a major source of opacity throughout the infrared and therefore must be accounted for in the retrieval of gaseous constituent abundances. Limb sounding, in particular, may have limited application in regions of dust storm activity.

(3) Constituent abundance and temperature sounding of the outer planets.

The outer planets present a particularly challenging application of passband radiometry due to the complex character of the spectra of these planets and the low flux levels encountered. In general, there are few broad spectral intervals which do not contain spectral features from two or more molecular species. Consequently, the retrieval of atmospheric parameters from pass-band observations is more difficult than from observations which resolve the individual components of the spectrum. Prior knowledge of all radiatively active constituents, including aerosols, within an observed spectral interval is necessary.

Temperature sounding of the tropospheres of Jupiter and Saturn by pass-band radiometry is an accepted technique. Hence, the 50-600 cm^{-1} emission features of collision-induced H_2 and the 1306 cm^{-1} band of CH_4

may be used in tropospheres above the cloud tops. High spectral resolution is unnecessary for this measurement, particularly in the relatively "clean" far infrared region. For the far outer planets the large energy grasp of filter radiometry is essential and these instruments may be the only feasible approach to sounding the atmospheres of Uranus and Neptune from flyby and orbiter missions.

The application of this technique to the outer planets is limited, in the same way as the low and intermediate resolution devices, to the region below the tropopause and above the cloud tops.

Critical Hardware Needs

Because many filter radiometers have been built and flown, we have identified only three areas of hardware requiring long-term development activities. These are for infrared filters, both cooled and uncooled; improved detectors, both single element and arrays; and light-weight cryogenic systems. The latter two requirements are common to virtually all classes of infrared instruments.

Evaluation Summary

Filter radiometers are relatively simple, light-weight and robust devices which have a substantial heritage of successful implementation in planetary investigations (see Chapter II). Radiometers have been shown to be of particular value in remote sensing of atmospheric temperature, gaseous species abundances and their vertical, lateral and temporal variability; cloud macrostructure; surface temperature; and in energy budget studies of planets for which the basic composition and state of the atmosphere was previously known. Clear advantages exist over other infrared experiment techniques wherein phenomena are observed in conditions of low flux levels or in short integration times. The intrinsic energy grasp of these devices is largely due to the $\Delta\lambda/\lambda \geq 1\%$ pass-band and the consequent large etendue. Furthermore, such a large spectral bandwidth encompasses many lines from the absorption or emission bands of a molecule.

III - 2. IMAGING INFRARED SPECTROPHOTOMETER

This is a class of instruments capable of photometric imaging of planetary bodies in the infrared with low-to-medium spectral resolution ($\lambda/\Delta\lambda$ = 50-500). Spectral resolution of this order is sufficient for the identification and determination of abundance of some species in outer planet atmospheres. The spectral selection may be accomplished in a variety of ways including the use of filters, a circular variable filter, an interferometer, or a dispersive system. Three types of detectors yield different imaging modes: (1) Single element detectors. An image is constructed by the raster scanning the object across the detector(s). This configuration was used on Pioneer Venus by the Orbiter Infrared Radiometer to produce multi-wavelength images of Venus. (2) One-dimensional arrays; these allow either a multiplexed extension of the raster scan technique to multiple wavelengths (e.g. the Galileo NIMS instrument) or a reduction of the raster scan to a single sweep. (3) Two-dimensional arrays; these allow either simultaneous imaging of the entire focal plane or single line imaging in multiple wavelengths using a dispersive system.

Multispectral infrared imaging has been performed from Earth for sometime; near Earth-orbit missions do not pose any new problems which are not already addressed by the Infrared Astronomical Satellite program (IRAS) and by the Shuttle Infrared Telescope Facility (SIRTF) study. We review here the observational capabilities of imaging infrared spectrophotometers from near Earth-orbiting facilities and on near-target, flyby and orbiter missions. Such instruments have application to planetary geology as well as atmospheric studies, since combined spatial and low resolution spectral mapping in the near infrared allows mineral province identification and studies of surface heat flow.

Instrument Specifications

The capabilities of imaging spectrophotometers for the measurement of planetary rotation, cloud macrostructure, winds (via cloud tracking) and variability of atmospheric species have been considered. Consequently, a variety of instrument configurations has been examined and the requirements for telescope aperture and measurement integration times identified.

The hypothetical instruments used in the model calculations fall naturally into two categories; the filter and dispersive systems in one and the Fourier transform spectrometer (FTS) in the other. This distinction is primarily a consequence of the existence of an instrument which was built for the Voyager Mission but was not included in the instrument complement at launch (IRIS was flown instead). MIRIS uses a pair of Michelson interferometers and a bore-sighted single channel radiometer. While the MIRIS instrument does not have an imaging capability it does provide a useful reference for performance estimates for instruments in this class covering the spectral range 60-2000 cm^{-1}.

Performance estimates in the near-infrared were made at 2.5 μm - the model instrument specifications are:

Collector: see examples

Detector Figure of Merit: $D^* = 8X10^{11}$ cm $Hz^{1/2}$ W^{-1}, $\lambda = 2.5$ μm

Cooling Requirements: $\lambda \leq 5$ μm (detector only)

In the spectral region ≥ 5 μm the specifications for MIRIS were used in the examples, they are:

Collector: 50.8 cm dia. (flyby spacecraft)

Instrument Noise Equivalent Radiance (W cm^{-2} sr^{-1}/cm^{-1});
Far IR interf. at 400 cm^{-1}, 1.3 - $2.9x10^{-8}$
Near IR interf. at 1300 cm^{-1}, 3.0 - $5.6x10^{-10}$
Near IR interf. at 2000 cm^{-1}, 1.9 - $3.5x10^{-10}$

Spectral Resolution cm^{-1} (apodized):
Far IR, 6.45 (mode 1)/1.7 (mode 2)
Near IR, 6.45 (mode 1)/2 (mode 2)

Time per Interferogram:
45.6 s (mode 1)/141.6 s (mode 2)

Cooling Requirements:
instrument operates at 140K

Applications Analyses

(1) Planetary rotation and global atmospheric activity.

In this experiment the objective is to determine the period of rotation of the visible surface of a planet or to measure the rate at which cloud features move over a planet which is obscured by cloud. Observations at 2.5 μm from near-Earth orbit of Uranus are practical using a collector of 3.2 m diameter with short measurement integration times ($\sim$1 sec.) - telescope size is defined by signal considerations since the planet disk does not fill the field-of-view.

(2) Cloud Macrostructure.

This phenomenon is best studied from flyby or orbiting spacecraft because of the high spatial resolution required. From a near-planet spacecraft both the near-infrared and MIRIS instrument models show some capability in sensing cloud macrostructure out to Uranus. In the near-infrared the measurement goal is the horizontal scale of the visible clouds; measurements in reflected sunlight are feasible out to Neptune. In the far infrared, measurements of cloud height and amount are certainly practical for Jupiter and Saturn. For Uranus, the acceptable measurement requirements might be met by the low resolution mode of the MIRIS model, but only if the vertical temperature profile can be determined with good accuracy.

(3) Wind via cloud tracking

As in the example given above, only very limited use of near-Earth orbiters may be made in the measurement of atmospheric motion from cloud tracking. In near-planet orbit, high spatial and temporal resolution images in the visible and near-infrared are exceedingly useful - evidenced by the results from the Voyager and Viking mission. Measurements of cloud motion may be extended to Uranus and Neptune in the near-infrared. In the thermal emission region (where the height of the cloud might be determined) the flux levels are too low for measurements of Saturn and the far outer planets with MIRIS.

(4) Vertical profiles of atmospheric temperature.

MIRIS had the desirable characteristics for tropospheric temperature sounding of Jupiter and Saturn from flyby and orbiter spacecraft. From near-Earth orbit a very large telescope (see Appendix D) would be required to meet the acceptable measurement requirements. Even in the low spectral resolution mode ($\delta\nu$ = 6.5 cm^{-1}) MIRIS would require integration times >1 hr. to perform temperature sounding of the troposphere of Uranus in the 100 - 300 cm^{-1} interval.

(3) Vertical, lateral and temporal variability of species.

For the outer planet tropospheres, this phenomenon is best addressed in the near infrared. However, scattering by clouds greatly complicates the analyses. From near-Earth orbit the MIRIS instrument would require a very large telescope (in excess of the aperture of Space Telescope, see Appendix D) to achieve the desired spatial resolution in the thermal infrared. The capabilities of MIRIS should be assessed relative to the recent performance of IRIS on the Voyager Mission flyby of Jupiter and Saturn. Significant advances over IRIS are necessary to warrant implementing MIRIS. The spectral resolution of IRIS is 4.3 cm^{-1} and for MIRIS it would be 1.7 cm^{-1} (apodized) in high resolution mode. To obtain adequate signal-to-noise at Uranus integration times of $\sim$12 hrs. would be necessary for MIRIS to acquire spectra in the intervals 50 - 500 cm^{-1} and 1000-2000 cm^{-1}; the latter in reflected sunlight.

Critical Hardware Needs

Infrared detector arrays (both 1 and 2 dimensional) are crucial. There is a need to gain experience in the use of infrared detector arrays in low spectral resolution infrared imaging systems. Radiation shielding of detectors and CCD multiplexers is an area requiring development.

Evaluation Summary

The capability of imaging with a spectrophotometer considerably enhances the science return from low-to-medium resolution spectroscopy. In the near infrared, the imaging capability makes possible the mapping of cloud motions, identification of horizontal cloud and haze distributions and the mapping of surface properties such as material identification and heat transfer processes. In the infrared and far infrared, low-to-medium spectral resolution imaging may be used for mapping temperature and, in a more limited sense, species abundances in planetary atmospheres.

Near infrared spectrophotometry of the planets and their satellites has been, at best, limited and constitutes a new and valuable science objective. In the thermal infrared the success of the Voyager IRIS instrument in performing low-to-medium resolution spectroscopy of Jupiter, Saturn, Titan the anticipated results for Uranus makes it unlikely that the modest improvement offered by MIRIS is worthwhile if we are to meet even the "acceptable" general goal of substantially new results. It appears that a new approach will be essential.

III - 3. MEDIUM TO HIGH RESOLUTION IMAGING SPECTRORADIOMETER

This instrument class includes all methods for achieving spectral resolving powers $\lambda/\Delta\lambda$ 20,000 with the capability of imaging. A number of instrument techniques may be used to obtain images with this spectral resolution. We have considered three such techniques: A dispersive system capable of simultaneous wavelength coverage and one-dimensional imaging, a tunable Fabry-Perot spectrometer capable of two-dimensional imaging: and a Fourier transform spectrometer (FTS) with simultaneous wavelength coverage and one or two dimensional imaging capability. We have placed strong emphasis on imaging with this class of instruments because there is both a substantial improvement in science return from thermal and composition "maps" and there have recently been rapid developments in two-dimensional detector array technology which begins to make their use practical.

The detailed treatment of imaging spectrometers presented here is relevant to a dispersive system. However, the capabilities of the dispersive system are also those of a Fabry-Perot system - with the exclusion of simultaneous imaging and wavelength coverage, as stated above. An overview of the Fourier transform spectrometer approach is also given with specific capabilities mentioned where appropriate. Whereas the current analysis only illustrates measurements made near 5 μm, this instrument class encompasses spectrometers which operate throughout the infrared.

Instrument Specifications

Observations from large near-Earth orbiting telescopes and from flyby and orbiter spacecraft (all collectors at 290K) are evaluated for the following instrument description.

Collector: See examples
Detector figure of merit: NEP = 1×10^{-16} W $H_z^{-1/2}$, $\lambda\geq5\mu$m: 2-D array

Etendue: A = 6.95×10^{-10} m^2 sr, 30 cm grating (or 1.5 mm aperture FTS/Fabry-Perot. Systems matched throughout.

Spectral Resolution: $\lambda/\Delta\lambda$ = 20,000 (0.1 cm^{-1} at 5 μm); 1% filter band pass N.E.I., W m^{-2} $sr^{-1}(\delta\nu)^{-1}s^{-1}$:

7.2×10^{-6} at 670 cm^{-1} and

1.4×10^{-6} at 2200 cm^{-1} (dispersive system)

The system used in the following examples has the spectrometer operating at 120 - 145K and the detector package (including filter, baffles and condensing optics) at less than 50K.

The main discussion presented here centers on a spectroradiometer whose characteristics (e.g. etendue, efficiency, detector NEP) are defined by internal considerations of resolving power and required signal/noise. No attempt was made to operate the collector in a diffraction-limited mode, entirely appropriately for small-collector systems on a planetary flyby or orbiter but less desirable for the major Earth-orbiting telescopes expected to be available in the next decade.

The diffraction-limited spatial resolutions of SIRTF and ST are shown in Table III-1 for four frequencies. Only ST on Jupiter between 5 and 10 µm meets the R/20 measurement requirement although it is evident that in the 1-5 µm region ST will be excellent on all the planets out to Saturn. SIRTF is primarily intended for long wavelength use and appears to be so limited in its applicability that we hesitate to recommend specific instrument developments for its use. However, there is no doubt that the employment of existing SIRTF instrumentation on planets could be valuable.

Applications Analyses

The application of a dispersive spectrometer has been considered for the mapping of species variability in the tropospheres of Jupiter and Saturn; tropospheric temperature sounding on Jupiter and Saturn, and the detection of minor constituents on Venus. These examples illustrate the capabilities of medium to high resolution dispersive and Fabry-Perot spectrometers for a wide variety of applications from both near-Earth orbiting telescopes and near-planet observations from flyby or orbiter spacecraft.

1) Species variability (temporal or spatial) in the tropospheres of Jupiter and Saturn.

The required spectral resolution was taken to be that which is sufficient to investigate tropospheric structure in these planets. The value of 0.1 cm^{-1} was judged adequate, since:

i. Typical linewidths in tropospheric spectra are ~0.1 cm^{-1}.

ii. Investigations of Jupiter by Beer and Taylor (1972, 1973a, 1973b) using spectral resolutions of 0.2, 0.1 and 0.05 cm^{-1} in the 5 µm window showed:
   a) that the benefit of using 0.1 rather than 0.2 cm^{-1} is substantial: significantly more spectral structure is revealed but
   b) that the improvement by using 0.05 cm^{-1} is quite small and hardly worth the loss in signal/noise.

iii. Model spectra of Jupiter and Saturn confirm that substantially all the useful information can be extracted with 0.1 cm^{-1} resolution.

TABLE III-1

DIFFRACTION LIMITED SPATIAL RESOLUTION FROM EARTH ORBIT

R = Planet Radius; Spatial Resolution Requirement $\leq$ R/20 (per Chapter I)

MISSION	SIRTF					ST					
Aperture (m)	0.85					2.4					
Freq. (cm^{-1})	670	1400	1800	2200	4000	670	1400	1800	2200	4000	
Wavelength (μm)	15	7	5.6	4.6	2.5	15	7	5.6	4.6	2.5	
PLANET											COND.
Venus	R/2	R/3	R/4	R/5	R/9	R/4	R/9	R/12	R/15	R/27	E
Mars	R/2	R/4	R/6	R/7	R/13	R/6	R/12	R/16	R/19	R/35	0
Jupiter	R/5	R/11	R/14	R/17	R/31	R/15	R/31	R/39	R/48	R/87	0
Saturn	R/2	R/4	R/6	R/7	R/13	R/6	R/12	R/16	R/19	R/35	0
Uranus	2R	1R	1R	1R	R/2	1R	R/2	R/3	R/4	R/7	0
Neptune	4R	2R	2R	1R	R/2	2R	1R	R/2	R/2	R/4	0

E = Maximum Elongation

0 = Mean Opposition

The performance of the model cold dispersive spectrometer (ambient temperature 12.5 cm aperture telescope, 142K spectrometer, 49K detector and 1% band pass filter) was investigated for the specific case of determining the variability of CH_3D in Jupiter and Saturn. A spacecraft platform at 10 R_{planet} at Jupiter was assumed. The P7 manifold of CH_3D at 2144 cm^{-1} was used.

For Jupiter, measurement integration times of 1 second give minimum detectable abundance changes in CH_3D of $\leq$ 5% near the 1 bar atmospheric pressure level. For Saturn, an integration time of 10^4 seconds is required for minimum detectable abundance changes of $\lesssim$ 10% near the 1 bar level.

For the same measurement scenario the cold Fourier transform spectrometerinstrument model (ambient temperature telescope, 142K FTS, 49K detector) was shown to require integration times of between 100 and 500 times longer to achieve the same level of performance in this experiment. The FTS is viable only if operated with a cold telescope or if the warm telescope is followed by a cooled post-disperser - which reduces the simultaneous wavelength coverage.

The Fabry-Perot spectrometer measurement characteristics would be the same as those for the dispersive system. A two-stage Fabry-Perot would consist of a cold high resolution stage and warm order isolating stage using an ambient temperature telescope. The spectral pass band would be stepped over the desired interval.

2) Tropospheric temperature sounding of Jupiter and Saturn.

Using the same instrument models as those in the previous example, the sounding of outer planet temperature using the P7 manifold of CH_3D was explored. Temperature sounding of Jupiter in the 0.1 bar to 4 bar pressure interval is eminently practical. The recent Voyager IRIS experiment has demonstrated the practicality of this measurement in numerous spectral regions with a resolution of $\delta\nu = 4.2$ cm^{-1}; similarly for Saturn. However, the current example serves to illustrate instrument capabilities at much higher spectral resolution. Resolving powers of 20,000 may be essential, particularly when working in spectrally complex regions. At this resolution measurement integration times of 1 sec are necessary to achieve noise equivalent temperatures $\leq$ 1K throughout the Jovian troposphere using the model dispersive instrument. Both of the desirable measurement requirements for spatial resolution (vertical and horizontal) can be met in an imaging format from orbiter or flyby spacecraft. At Saturn the integration times increase to 10^4 seconds for equivalent measurement precisions.

3) Detection of DCl on Venus.

The detection of DCl is an interesting goal for Venus because it is conjectured that the D/H ratio may be a factor of 100 or more enhanced due to preferential H escape. A number of lines of the 1-0 band of DCl are suitable for detection in the 2100 cm^{-1} region.

Calculations for the hypothetical dispersive system show that an effective S/N of 2000 can be achieved ($\tau = 10^4$ s) with a minimum detectable equivalent width of $5 X 10^{-5} cm^{-1}$. The strongest lines in the 1-0 band have a strength of $1 X 10^{-19}$ cm^{-1} mol^{-1} from which we deduce that the minimum detectable column abundance of DCl is $5 X 10^{14}$ mol. cm^{-2}.

Now the measurements of Connes et al (1967) on HCl show a total HCl column of $1.5 X 10^{18}$ mols. whence the minimum detectable DCl /HCl ratio is ~ $3 X 10^{-4}$. While this is a factor of 10 above the canonical solar system value of $2-5 x 10^{-5}$, a factor of 100 enhancement would be readily detectable with the instrument from either near-Earth or near-Venus spacecraft.

Critical Hardware Needs

While improved detectors are a critical element in most advanced infrared instruments an imaging spectrometer (of any type) necessarily employs a detector array. Prototype 32 x 32 arrays are now available for the region below 5.5 m but their performance does not yet meet that of individual detectors, and arrays for longer wavelengths are developmental at best. Obviously, the availability of large detector arrays (preferably with CID or CCD on-chip processing) is the single most critical element in any such system.

The feasibility of medium to high resolution spectrometers in spacecraft missions is also dependent upon the development of lightweight, cooled instrumentation.

The system envisaged here has the band-pass spectrometer operating at 120-145 K and the detector package (including filter, baffles and condensing optics if used) at less than 50 K. Thus there must be two cooling systems, although one would undoubtedly "stage" the lower temperature by the higher. A saving factor is that the mass and volume of the detector package is probably far less than that of the spectrometer itself.

The nature of coolers will be highly mission-dependent. In deep space radiative coolers are effective and can certainly provide the "system" temperature of 120-145 K within the current state-of-the art. In near-Earth orbit stored cryogens become attractive. Solid methane/ammonia coolers (63/152 K) have been flown in space and a 3-year lifetime CH_4/NH_3 system is to be used on the Gamma Ray Observatory. Solid N_2 and CO_2 are also good candidates. Venting them directly to space achieves ambient pressures (at the cryogen surface) of 10-20 Torr giving temperatures of < 49 K and < 142 K respectively. These cryogens can be manufactured from high-pressure gas in situ so that they might be attractive for missions with long cruise times.

Evaluation Summary

The spectral resolving power which defines this class of spectroradiometers ($\lambda/\Delta\lambda = 20{,}000$) is sufficient to extract substantially all of the useful tropospheric information for Jupiter and Saturn. The model calculations have shown that tropospheric temperature and minor constituent abundances on Jupiter and Saturn may be determined with such instruments on spacecraft and using near-Earth orbiting telescopes of the size of ST or larger.

From the study of dispersive, Fabry-Perot and FT spectrometers we deduce that :

a) the cold FTS, or warm band pass system is totally background limited at all wavelengths unless the effective emissivity of all elements preceding the detector can be reduced to ~ 10^{-3} or less.

b) the cooled dispersive and Fabry-Perot systems are detector noise limited at all wavelengths below 7 μm and could be at longer wavelengths if either the effective emissivity can be reduced to < 5% or the instrument temperature lowered to ~ 120 K or some combination thereof.

c) the cold FTS becomes a viable device only if attached to a cold telescope or is followed by a cooled post-disperser (i.e. essentially the dispersive system assumed here as a stand-alone system).

d) the advantages of the cooled dispersive and Fabry-Perot systems are a factor of 10 in N.E.I. or a factor of 100 in measurement times.

e) in cooled dispersive and Fabry-Perot systems the temperature of the telescope is essentially irrelevant because at wavelengths where its background exceeds that of the spectrometer, both are negligible anyway.

Elementary computations of signal-to-noise ratios show clearly that medium to high resolution spectroscopy is ruled out for nadir sounding of the far outer planets because one cannot meet the phenomenon measurement requirements of spatial and temporal resolution. However, useful survey spectroscopy of the far outer planets can be performed.

III - 4. HIGH RESOLUTION INFRARED SPECTROMETER

The characteristics of this instrument class are:

- A minimum of 1 percent photometric accuracy (i.e., minimum signal-to-noise ratio of 100:1 and comparable calibration).
- Spectral resolution significantly smaller than the pressure broadened spectral line width.
- Full spectral coverage from 1 to 50 μm is desirable. This corresponds to the range of interest for most currently identifiable candidates for spectral searches. A restricted spectral range of 1.5 to 15 μm would be acceptable for many of the likely molecular species.

Devices of this type are suitable for the detection of new species in planetary atmospheres. Applications also include the detailed study of the physical state of atmospheres and vertical sounding of known species. We have assumed the use of this instrument class in conjunction with a telescope in near-Earth orbit to provide the performance estimates which follow since its use in flyby and orbital missions was considered inappropriate by the working group. An exception to this is the promising application of solar occultation spectrometry for species detection in the atmospheres of the far outer planets.*

Instrument Specifications

In order to examine the capabilities of high resolution infrared spectrometers we have chosen to model a Fourier Transform Spectrometer (FTS) which employs a large aperture telescope in near-Earth orbit. We are aware that there are many ways of achieving the required spectral resolution; the performance results presented here for an FTS will be, in general, applicable to all such instruments.

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*Detailed calculations of the expected signal-to-noise ratio from Uranus, Neptune, Titan, etc., show, unequivocally, that passive spectroscopy beyond the region where solar reflection is significant is not viable at spectral resolutions necessary to perform detailed atmospheric studies. Solar occultation experiments seem to us to offer significant advantages for the investigation of atmospheres above the main cloud deck. Even at the distance of Neptune the Sun subtends ~1 arc min., well above the diffraction limit of even modest sized collectors at $\lambda = 20$ μm. Furthermore, the viewing mode is that of a limb sounder, offering excellent height resolution and increased sensitivity to minor constituents because of the very long path lengths. Since it may be expected that the Sun will fill, or nearly fill, the field-of-view of the spectrometer, signal-to-noise ratio is not a problem. We recognize, however, that such an experiment places severe demands on all aspects of the mission and orbiting spacecraft systems.

Collector area: 4.0 m^2 (cryogenic)

Detector Figure of Merit:

InSb; Detector T = 60 K; NEP^*_{limit} = 7.0×10^{-16}; $\lambda = 1$ m
InSb; 60 K; 1.8×10^{-16}; $\lambda = 4$ m
InSb; 4 K; 1.9×10^{-16}; $\lambda = 1$ m
InSb; 4 K; 9.3×10^{-17}; $\lambda = 5$ m
GeGa; 4 K; 2.6×10^{-16}; $\lambda \geq 5$ m

NEP_{limit} = zero-background NEP in $WHz^{-1/2}$

Spectral Resolution: $\leq 0.02\ cm^{-1}$

Spectral Coverage: 1 - 50 µm

Applications Analyses

Examples are given below to illustrate the application of FTS to the detection and determination of abundance of new species; the determination of planetary rotation and global-indices of atmospheric activity; the measurement of vertical, lateral and temporal (VLT) variability of species; and sounding of atmospheric temperature and pressure.

i) Detection and abundance of species

For this experiment there is no inherent requirement for spatial resolution - indeed with the assumed 2.4m telescope, the far outer planets do not fill the available field of view. The required signal-to-noise ratio for the spectra at a spectral resolution of $\delta\bar{\upsilon} = 0.02\ cm^{-1}$ is taken to be S/N = 100. Undiscovered species might, for example, be expected on Titan, Uranus and Neptune. For Uranus and Neptune, at all infrared wavelengths, our study has shown the search for species to be impractical even with a cooled telescope of the size of Space Telescope (2.4 m) due to detector noise. The integration times for these planets are typically much in excess of 1 month.

Although cooling of the InSb detector to 4K reduces the NEP out to 4 µm, the detector remains the dominant source of noise throughout its applicable spectral region. Even if this noise source could be reduced by the one to three orders of magnitude necessary for photon-noise to become the dominant factor, the light levels encountered for the far outer planets are so low that integration times are intolerably long. Substantial reduction in the requirements for signal-to-noise, spectral resolution would be necessary to make this a possible experiment.

Beyond 5 µm, the situation would become less problematic in the unlikely circumstance, that detectors of NEP$\leq 10^{-17}$ $WHz^{-1/2}$ became available. From 10 µm outward, spectroscopy of Titan, for example, would be photon-noise limited and integration times quite short (t<<1 hr) for our hypothetical instrument.

While not considered here in detail, the search for unknown species and abundance determinations in the atmospheres of Jupiter and Saturn appears to be practical throughout the spectral region 1 to 50 μm for our experimental arrangement with good signal-to-noise and high spectral resolution.

1) Planetary rotation and global atmospheric activity

Photometric or radiometric calibrations are required to monitor the expected albedo and thermal flux changes which may be linked to planetary rotation and atmospheric activity (see Chapter II for phenomenon measurement requirements). As noted in the discussion of species detection given above, the 1% precision requirement in flux calibration at $\lambda \leq 4$ μm is not consistent with high-resolution spectroscopy in reasonable integration times for the far outer planets. However, by sacrificing spectral resolution, the FTS can meet the 5-minute time constant requirement for the observation of this phenomenon. It is important to note that the line width information would be lost as a consequence of reducing the resolution. Certainly, if this is the primary observational goal of an experiment is this phenomenon, then an instrument with intrinsic photometric and radiometric precision and low spectral resolution is preferred (see sections III - 2 and III - 3).

2) Vertical, lateral and temporal (VLT) variations of species

The determination of the VLT variations in the distribution of species requires measurements having moderate precision (5-20%), and short time constants ($t \leq 1$ min). At somewhat reduced spectral resolution, the lower signal-to-noise ratio requirements put tropospheric observations within the capabilities of the hypothetical FTS except for the far outer planets. The requirement for spatial resolution does, however, set strict limitations on the minimum acceptable telescope aperture. For diffraction limited spatial resolution from Earth orbiting telescopes the minimum aperture for a spatial resolution of $R_{planet}/5$ on Uranus is 3.4m diameter at 5 μm and 12 m at 15 μm. (The desirable spatial resolution for this phenomenon is $R_{planet}/20$). However, for Jupiter a collector aperture of 2.4 m (equivalent to Space Telescope) gives a spatial resolution of better than $R_J/30$ and for Saturn better than $R_S/10$ for $\lambda \leq 7 \mu m$. The instantaneous band-pass of the FTS system may be reduced to the order of 1% if only a few specific molecular species and bands are observed, thereby reducing the requirement for telescope cooling.

3) Temperature and pressure profiles

A high-resolution spectrometer may be used to study the temperature and pressure distribution of a planetary atmosphere through observations of detailed line shapes of a number of molecular species having a wide range of absorption strengths. In this experiment, the observations require the highest possible spectral resolution and signal-to-noise ratio, and the results are somewhat model dependent. Consequently, the instrument requirements and associated limitations are similar to those given above in the discussion of the detection and abundance of species with the added requirement of spatial resolution as small as R/20. Applications of this class of instrument for the measurement of temperature and pressure from line shapes are consequently limited to Saturn, Jupiter, Mars and Venus.

Critical Hardware Needs

The feasibility of this class of instruments for planetary studies depends on the development of lightweight coolable optics and marked improvements in infrared detectors.

Evaluation Summary

We find that high-resolution spectroscopy from near-Earth orbiting telescopes of the 2 to 4 m diameter is feasible for high signal-to-noise measurements of Venus, Mars, Jupiter and Saturn.

To extend our capabilities to the far outer planets, novel observation approaches should be considered. Even for Saturn, a flyby or orbiting instrument may find limited application due to the long integration times required for high signal-to-noise spectrum at 0.02 cm^{-1} resolution.

An alternative, and potentially attractive, approach is the use of a high-resolution instrument in a solar occultation configuration. Observations of the Sun made through the limb of the atmosphere of the planet from an orbiting spacecraft provide an experimental approach which may be the only practical means of obtaining high resolution infrared spectra of Uranus and Neptune with sufficient signal-to-noise and spatial resolution to permit detection and measurement of minor constituents.

III - 5. CORRELATION SPECTRORADIOMETER

Correlation spectroradiometers are unique in the way they achieve both very high spectral discrimination and a large energy grasp. These devices work by correlating the observed atmospheric spectral lines (in emission or absorption) with a reference spectrum generated within the instrument. The most common and successful technique is to correlate the spectrum of a gas in the atmosphere with the spectrum of the same gas in a cell within the instrument. Another approach uses a grating with a mask in the focal plane to select the spectral intervals of interest. In this review of correlation spectroradiometers we treat only gas correlation spectroscopy.

The spectral resolution of gas correlation spectroradiometers is approximately equivalent to the width of the spectral lines of the gas observed ($\lambda/\Delta\lambda \sim 10^6$ for Doppler broadened lines). Narrow-band filtering is used to pre-select the spectral interval (usually 10-100 cm^{-1}) which contains lines of the atmospheric constituent of interest. Since the absorption spectrum of the gas in the cell matches line for line the spectrum of the gas in the atmosphere there is both a high degree of selectivity of that gas and an energy contribution from all correlated parts of the spectral interval to the measured signal.

The flight heritage of these devices is considerable. The Nimbus 4, 5 and 6 and TIROS N spacecraft have carried gas correlation spectroradiometers for temperature sounding of the Earth's stratosphere and mesosphere. The stratospheric and mesospheric sounder aboard Nimbus 7 is currently monitoring the vertical distribution and abundance of CO, NO, N_2O, H_2O, CO_2 and CH_4, as well as performing temperature sounding of the Earth's atmosphere. The first planetary instrument to use gas correlation techniques was the Pioneer Venus Orbiter Infrared Radiometer which used a CO_2 cell to sound temperature in the 90 - 130 km altitude range.

Gas correlation spectrometers are best used on flyby and orbiter spacecraft for the study of physical and species-specific chemical properties of planetary atmospheres. The instruments have greatest applicability to atmospheric pressure regimes in which Doppler line broadening is dominant and local thermodynamic equilibrium exists. Searches for as yet unidentified constituents of atmospheres are not feasible since instrument cell gases must be pre-selected.

Instrument Specifications

There are a variety of approaches used in gas correlation spectroradiometry and while the basic technique is the same in each, the instrumental details are very different.

Pressure Modulation Radiometry:

In this approach the instrument contains a cell of gas in which pressure is cycled about a mean value by a resonant piston. The incident atmospheric radiation passes through the cell on its way to a detector. As the pressure in cycled emission from the atmospheric gas is modulated. Continuum emission and emission from other molecular species is uncorrelated and thus largely unmodulated; hence radiation from a single molecular species may be selected. The cell absorption line shapes may be changed to suit the atmospheric path under observation by changing the mean pressure of the gas in the cell using a molecular sieve. Pressure modulation was used on the Pioneer Venus Orbiter Infrared Radiometer and the Nimbus 6 and 7 gas correlation instruments. The Nimbus 7 instrument contained seven pressure modulators with up to 3 in series using a single detector.

Selective Chopping Radiometry:

In this approach two cells, one containing gas and the other empty, are alternately placed in the optical train. This "chopping" of the incident radiation is equivalent to the pressure modulation described above except here multiple cells of static pressure are used. Although this approach has a minimum of mechanical complexity it suffers from difficulties in radiometric balancing and less flexibility when compared with pressure modulation.

Frequency Modulation Radiometry:

This is an outgrowth of recent developments in electro-optic and acousto-optic frequency translators in the infrared. In principle this approach is fundamentally more flexible than either pressure modulation or selective chopping and it has potential for measuring atmospheric winds directly. In operation the atmospheric spectral lines are shifted in frequency about the corresponding cell gas line-centers by approximately one half width. This frequency dither introduces a modulation in the detected signal. By altering the magnitude of the dither the part of lines sensed may be selected with high precision. This feature may permit the detection and measurement of atmospheric winds since relative motion between the instrument and atmosphere alters the superposition of the line centers of the atmosphere and cell.

In the numerical experiments which follow, the pressure modulator radiometer approach was used, with the exception of the discussion of the wind sensor.

Collector: 40 cm diameter (Saturn)
3 cm diameter (Mars) at 250 K

Detector Figure of Merit: 1x16 elements, 100μm x 100μm (Hg Cd)Te, (80K)

$$D^* (1320\ \mathrm{cm}^{-1}) = 5\times10^{11}\ \mathrm{cm\ Hz}^{1/2}\ \mathrm{W}^{-1}$$

$$D^* (820\mathrm{cm}^{-1}) = 4\times10^{10}\ \mathrm{cm\ Hz}^{1/2}\ \mathrm{W}^{-1}$$

$$D^* (680\ \mathrm{cm}^{-1})\quad 1\times10^{11}\ \mathrm{cm\ Hz}^{1/2}\ \mathrm{W}^{-1}$$

Spectral Resolution: $\Delta\nu \sim 10^{-3}\ \mathrm{cm}^{-1}$ in 10 - 30 cm^{-1} pass-band
(by pressure modulation)

Applications Analyses

Two experiment scenarios have been used to evaluate the capabilities of gas correlation spectroradiometers for outer planet and terrestrial planet atmospheres. The first is a pressure modulator radiometer orbiting Saturn (calculations performed for spacecraft at $4R_s$) making measurements at the nadir and at the limb of stratospheric temperature and species abundances. The second experiment employs a pressure modulator radiometer in a 300 km orbit around Mars for tropospheric and stratospheric measurements of temperature, species abundance and winds.

1) Stratospheric temperature sounding of Saturn.

Sounding of temperature above the thermal inversion near 60 mb on Saturn poses a considerable challenge to remote sensing techniques. In the pressure height interval 60 - 0.1 mb the atmospheric temperature increases from ~90K to ~160K. Soundings of the middle and lower stratosphere must be made by viewing through the relatively hot upper stratosphere. If these upper layers contribute appreciable opacity in the observed spectral interval, then the radiant energy observed will be dominated by flux from the upper atmosphere. The choice of constituents useful in temperature sounding of Saturn is apparently limited to H_2 and CH_4. Collision induced hydrogen spectral features in the far infrared may be used for sounding of the troposphere where the pressure exceeds 100 mb. Methane may be used throughout the atmosphere above the cloud tops. However, the useful CH_4 spectral band (ν_4) is near 8 m whereas the peak in the thermal energy from Saturn occurs near 20 μm. Our study has shown that an instrument must have spectral resolving power $\lambda/\Delta\lambda \approx 10^6$ in order to select the near-wings of the CH_4 spectral lines so that the thermal emission of the line cores from the upper stratosphere does not dominate the observed flux.

Numerical modeling shows gas correlation spectroradiometry to be well suited to temperature sounding of Saturn's stratosphere. The very high spectral resolution coupled with the simultaneous observation of 50 - 100 spectral lines of CH_4 in a 20 cm^{-1} interval gives good signal-to-noise and height discrimination throughout the stratosphere. In a limb viewing geometry, measurement integration times of <10 sec give noise equivalent temperatures of <1K and spatial resolution well within the desirable measurement requirements for this phenomenon. Non-LTE effects probably limit the application of this technique to the region where the pressure is $\geq$ 0.05 mb.

2) Vertical abundance profiles and vertical, lateral and temporal variability of minor constituents in the stratosphere of Saturn.

For this study, we chose to examine the capability of gas correlation devices in determining vertical profiles of ethane (C_2H_6) abundance over the planet. Since species abundance measurements in thermal emission require knowledge of the atmospheric temperature at each of the levels observed, the stratosphere of Saturn presents a particularly difficult case. The feasibility of temperature sounding with correlation devices (see previous example) and models of instrument performance for the current example show 10%

accuracy in sounding the vertical abundance profile of C_2H_6 in the 10 - 0.1 mb pressure height interval. For limb sounding measurement integration times of 10 seconds and vertical resolution of ~ 1/2 scale-height in a horizontal field-of-view of ~ 1000 km give signal-to-noise ratios of >150 for 5 to 0.2 mb pressure height.

3) Atmospheric temperature sounding of Mars

In this experiment, the performance of gas correlation spectroradiometers was evaluated for sounding temperature on Mars from the surface through the mesosphere (~ 10 - 10^{-3} mb). CO_2 was used as the sounding species in a 20 cm^{-1} pass-band interval near 620 cm^{-1}.

The strategy which provides the greatest vertical resolution and widest altitude coverage of the atmosphere is zenith scanning (nadir to limb). In the lower atmosphere, nadir sounding with gas correlation techniques provides ~ 1 scale height vertical resolution from the surface to about 45 km even in conditions of moderate dust loading of the atmosphere, such as in the period of decay of a major dust storm. Since this technique uses signal processing which permits the unmodulated signal (the pass-band flux) and the modulated signal (the correlated spectrum only) to be measured simultaneously, the surface and atmospheric temperatures can both be measured. This is of particular value when the temperature of the atmosphere very near the surface is to be measured. Conventional techniques are often severely hampered in this case because of contamination of the atmospheric measurements by large surface contributions to the observed radiance. Limb sounding provides coverage of the 25 - 65 km altitude range with very high vertical resolution (~1/2 scale height) using the 620 cm^{-1} spectral region. During periods of minimum dust loading (visible column dust opacity <0.1) limb temperature sounding may be performed down to the surface with the bands of isotopic CO_2 near 7-8 μm.

For the entire 0 - 65 km height range, the nadir and limb soundings give noise-equivalent-temperatures of <1K in <<1 min. measurement time with a spatial resolution of 5 km vertical by 80 km horizontal from an orbiter. Measurements of this type would provide global temperature field data which exceed all of the acceptable measurement requirements.

4) Abundance and vertical, lateral and temporal variability of water vapor on Mars.

Although the column abundance of water vapor was monitored by the Mars Atmospheric Water Detector on the Viking orbiter, no measurements of the vertical distribution of the water were made. The feasibility of employing gas correlation spectroradiometry for this purpose was examined.

Limb sounding with gas correlation methods in the spectral interval 1430 - 1440 cm^{-1} (near the infrared dust opacity minimum) is capable of water vapor abundance measurements down to the part-per-million level. Models of water and dust loading in the atmosphere of Mars suggest that measurement times near 10 seconds are adequate to obtain vertical profiles of water vapor from the surface to >30 km altitude. Measurements accuracies of 10 - 15% may be expected for 5 km vertical and 80 km horizontal spatial resolution.

During periods of dust storm activity, nadir soundings may provide low vertical resolution (1-2 scale heights) profiles of water vapor. With nadir and limb scanning capability, gas correlation spectroradiometry would permit global maps of the vertical, lateral and temporal variability of water vapor at all times except during the most intense dust storms.

5) Direct measurement of wind velocity on Mars

The possibility of making direct measurements of the zonal and meridional components of the wind field on Mars from a polar orbiter was investigated. The capability of gas correlation spectrometry in sensing wind on Mars may be extrapolated from the results of a program currently underway to develop a wind sensor for the Earth's stratosphere using the same technique. The atmosphere of Mars and the stratosphere of the Earth are in similar pressure and temperature regimes over a broad altitude range.

Wind-induced Doppler shifts in the thermal emission lines of a gas in the atmosphere are measured relative to absorption lines of the same gas in a cell within the instrument. Predicted accuracies for wind velocity measurements in the Earth's atmosphere are 3 - 5 m/s from 25 - 110 km altitude with 5 km vertical resolution using N_2O and CO_2 as "tracer species".

For Mars, CO_2 and H_2O might be used to span the altitude range from the surface to ~ 50 km in periods of low dust loading of the atmosphere. Since measurements of the atmospheric temperature or species abundance are not required to retrieve the vertical wind profile, the use of species having a variable distribution, such as water vapor, is permissible. Preliminary modeling of a hypothetical gas correlation spectrometer wind sensor indicates an accuracy of ~ 5 m/s in the wind velocity in the height range 0 - 50 km over Mars.

Critical Hardware Needs

The primary hardware development requirements for gas correlation spectroradiometry are: 1) gas handling and containment, and 2) frequency modulation. The design and fabrication of pressure modulation cells for future applications will draw heavily on the experience already gained from numerous successful flight experiments. However, if pressure modulators are to be used in outer planet missions the cells must be considerably longer than those previously built, the compression ratios must be higher and the gas must be contained for up to 12 years on missions of long duration (4-5 year gas containment is currently demonstrable). For all applications, methods for monitoring and controlling the cell gas need improvement. Pressure modulation cells which can be cooled to 150K are also needed.

Frequency translation appears to be a very promising technique for gas correlation modulation. This approach may offer substantially more flexibility than pressure modulation in some applications and a greater modulation of the cell gas spectral lines. Appendix A - Section X gives an overview of the various methods for obtaining frequency translation.

Evaluation Summary

We have evaluated the capabilities of gas correlation spectroradiometry for remote sensing of temperature and species abundances in the atmospheres of the terrestrial and outer planets, and the direct measurement of wind on Mars. This technique appears to have unique capabilities in each of these areas due to the combination of very high spectral discrimination and large energy grasp. For temperature and minor constituent abundance profiling in the stratosphere of Saturn the gas correlation technique is well suited to high spatial and temporal resolution measurements - we have found no other practical approach to these measurements. For Mars, vertical profiles of water vapor and temperature can be obtained in the troposphere and stratosphere using this technique. Of particular importance for Mars is the technique's virtual rejection of atmospheric continuum (dust) emission and absorption. Preliminary analysis also shows that the atmospheric wind field on Mars may be measured directly using gas correlation spectrometry.

III - 6. HETERODYNE SPECTROMETER

Heterodyne detection techniques provide very high spectral resolution. Spectral line profiles may be measured in emission or absorption at resolutions which are small with respect to Doppler line widths. Direct measurements of kinetic temperature are possible, for example, making temperature sounding practical in conditions when local-thermodynamic equilibrium (LTE) does not hold. If several lines are measured, the rotational excitation temperature can also be determined. Thus, conditions of non-LTE can be identified and studied. In addition, problems of blending and line operlap are minimized if fully resolved lines are available for analysis.

Heterodyne detection is performed by mixing photons from the remote source with those of an intense local oscillator in a non-linear photo-mixer (e.g. (HgCd)Te). A beat frequency signal is generated (the IF) over the response bandwidth of the mixer (> 2 GHz for the best (HgCd)Te detectors). The IF is amplified and may be mixed again (super-heterodyned) to place the IF frequencies in the range of a pretuned set of rf filters (filter bank) familiar to radio astronomers, or of an acousto-optical filter bank (under development at GSFC). The entire IF spectrum may be recorded simultaneously at the desired resolution giving a multiplex advantage. Furthermore, more than one simultaneous resolution can be chosen. To examine other spectral regions, the local oscillator frequency is changed.

While some interesting experiments can be done using CO_2 lasers as local oscillators, a widely tuneable local oscillator is desirable. Widely tuneable lasers include spin-flip Raman lasers, CO_2-microwave mixed sources, and tuneable semi-conductor diode lasers. Waveguide CO_2 lasers have limited tuneability, < 1000 MHz) around each CO_2 line. Tuneable semi-conductor diode lasers (TDL's) hold the greatest promise (at this writing) as widely tuneable local oscillators for spaceflight use. Devices of this type have been fabricated which have several hundred cm^{-1} tuneabilty and more than 1 milliwatt single mode power, sufficient to achieve shot-noise limited operation. The tuning for a single laser is quasi-continuous, being truly continuous over each Fabry-Perot mode ($\sim 0.5\ cm^{-1}$) with discontinuous jumps between modes ($\sim 1\ cm^{-1}$).

Instrument Specifications

No specific design for a heterodyne spectrometer was evaluated by the working group. Ground-based astronomical devices have been operated successfully by various investigators (including Peterson, 1974 and Mumma, 1981) and balloon-borne heterodyne measurements have been made by Menzies (1981). The working group used a heterodyne spectrometer design proposed for the Upper Atmospheric Research Satellite as an indication of the feasibility for spacecraft operation.

Applications Analyses

1) Sounding of the atmospheres of Mars and Venus

Peterson *et al* first applied CO_2 laser heterodyne spectroscopy to Mars and Venus in the 10 μm CO_2 bands and discovered strong non-thermal emission peaks at the cores of the $^{12}C^{16}O_2$ lines, which on Venus were brighter (300K) than the continuum (220K). They used lines of $^{13}C^{16}O_2$ and $^{12}C^{16}O_2$ to measure winds in the Venusian atmosphere to an accuracy of 7 m/sec in a broad vertical interval 65 - 80 km altitude. Fitting of the broad absorption lines on Mars yielded temperatures and pressures in the lower atmosphere, although the fit was not good near line centers. Mumma *et al* have extended this work using their own measurements. They showed that good fits were obtained for the entire line profile to within ± 50 MHz of line center (where the non-thermal emission spike dominates) assuming LTE for some observations. For others, however, they find that LTE fails (for the upper state of the transition) in the lower 12 km of the atmosphere, possibly due to collisional quenching of (001) by H_2O. In recent studies Mumma *et al* have detected large apparent vertical winds on Mars and Venus; these may be due to non-LTE phenomena in the stratosphere.

These examples of ground-base measurements point to a potential use of heterodyne spectrometers on near-Earth orbiting telescope facilities.

2) Jovian Stratospheric Phenomena

Near 10 μm, significant work can be done on stratospheric emissions (e.g. C_2H_2, C_2H_6) on Jupiter, and on non-thermal emission (e.g. polar aurorae and NH_3 masers) at sub-Doppler resolution. Mumma *et al*. have detected the Jovian continuum emission (~ 120 K) using 25 MHz bandwidth, with S/N ~ 2 after 3500 sec. integration. If the spectrometer had been used in the photometric mode (3 GHz) bandwidth, the S/N ratio would have been ~20.

The situation improves dramatically with increasing wavelength due to increasing etendue $(\sim\lambda^2)$ and to the Planck function. At 28 μm, the S/N ratio would be 1000/1 for 25 MHz resolution and 3600 sec integration. Development of local oscillators and photomixers for the 15-30 m range is being funded by the Goddard group, with special emphasis on the H_2 (2-0) line at 28.2 μm.

Critical Hardware Needs

Space qualified tunable systems are required as well as 15 to 30 μm mixers. A development effort in integrated optics at GSFC promises to relieve the problem of large weight and power consumption by rf electronics. The device under development is an acousto-optic spectral line receiver, which has been successfully deomonstrated in a laboratory brass-board version. Using non-integrated optics, this device provides 1024 channels over a 300 MHz bandpass and shows better stability than rf filter banks. A 1000 MHz Bragg cell is being prepared for testing and an integrated optics version is being developed under contract. The ultimate goal is to provide 1024 channels with 1 GHz band-width for less than 0.5 Kgm and one watt of power consumption. Such a device would enable significant reduction in the weight and power of spaceflight heterodyne spectrometers.

Evaluation Summary

Ground-based astronomy, aircraft and balloon observations have demonstrated the feasibility and usefulness of heterodyne techniques in obtaining very high resolution infrared spectra of planetary atmospheres. The most broad application of these devices would be on large aperture near-Earth orbit telescopes rather than on deep space missions. Observations of the planets out to Saturn would be practical with such a system, however, Titan and the far outer planets are not accessible due to signal-to-noise limitations.

III - 7. ENTRY PROBE SPECTROMETER

It is widely believed that a gas chromatograph and a mass spectrometer on an entry probe into a planetary atmosphere suffice to define the atmospheric composition quite well. However, the conflicting and ambiguous results from two such instruments on the Pioneer Venus entry probe have shown that this idea is incorrect. Some of the limitations and problems encountered with these two instruments are given below:

Mass spectrometer

The fundamental limitation of the mass spectrometer is that it can only measure radicals and ionized molecular fragments. For this reason it does not always yield a unique identification of the parent molecule and, unexpected molecular fragments cannot always be uniquely assigned. The pumping requirements for measurements at high atmospheric pressures may exceed the instrument capabilities; this was the case for the Pioneer Venus entry probe instrument. Outgassing of the pump was also a problem. The Pioneer Venus instrument used CH_4 as a mass calibration which, in the CO_2 oxidizing atmosphere of Venus, produced secondary reactions. The instrument also became plugged during descent by an aerosol particle.

Gas Chromatograph

Satisfactory use of this instrument relies critically on calibration of transit times and the uniqueness of transit times for the various gases encountered. In the analysis of the Pioneer Venus gas chromatograph data CO_2, O_2 and Ar were confused. Discrimination worsens for longer transit times, necessitating several colums and increased instrument complexity for acceptable performance. The very broad and strong peak of the major atmospheric constituent of Venus (CO_2) may have masked other constituents. Unexpected peaks are generally difficult to identify. The Pioneer Venus instrument had difficulty detecting some of the important minor constituents; SO_2 was barely detected, and HCl and HF were not detected at all.

The shortcomings of these two techniques have shown that additional instrumentation is needed. It is not suggested that an entry probe spectrometer can overcome all the shortcomings of the other instrument, since it will have its own weaknesses. However, all three instruments working together would be complementary and result in a better understanding of planetary atmospheres.

Entry probe spectrometers would have three basic functions:

1. Detection and identification of minor constituents in the atmosphere
2. Measurement of mixing ratios
3. Determination of the vertical distribution of these constituents.

For all these functions an IR spectrometer is very well suited. Because of the unique spectral signatures of molecular gases, identification of speciescan be carried out in an unambiguous manner. The laboratory intensity of the bands can be used to determine the absorber amount and together with the total density yield the mixing ratio of the species. By taking continuous measurements as the instrument traverses the atmosphere, the vertical distribution of the constituent can be established. These functions can be expanded to include the radiative flux profile of the atmosphere and the cloud and condensible species composition. Thus, if an instrument is designed that can look at the direct sunlight and total downward streaming diffuse light, or the upward flux of thermal radiation, the instrument can help in determining the radiative flux profile in the atmosphere. If the spectrometer is used together with a number of cryogenic surfaces, the frost point and identification of condensable species and the composition of the various cloud layers can be determined.

A variety of spectroscopic detection methods are feasible: photoacoustic spectroscopy, broad-band low-to-medium resolution spectroscopy, gas correlation spectroscopy, raman scattering and tuneable lasers among others. While our review of these approaches was necessarily based on the current state-of-the-art but we conclude that a conventional broad-band low-to-medium resolution IR spectrometer is presently the best choice.

The broad band low-to-medium-resolution spectrometer would likely be a conventional grating spectrometer or Fourier spectrometer. Since the instruments would be background limited and presumably use a bright light source, the Fourier spectrometer would not possess a multiplex advantag and by proper design of the source optics, the two instruments could have the same throughput, eliminating that advantage of a Fourier spectrometer. The Fourier spectrometer might have an advantage in a larger wavelength coverage. However, if infrared detector arrays become available, a grating spectrometer would acquire a multi-channal advantage which would favor its design. In any case, both instruments are technically quite feasible, but development and testing is needed to ensure that they would work in a probe environment.

The wavelength region to be covered by such an instrument should be fromabout 2-12 μm, since fundamental bands of most of the molecules known or expected to exist in planetary atmospheres occur in this wavelength region. However, significant results could be obtained with a spectrometer covering only 2-6 μm.

The sampling technique in a foreign atmosphere with upper atmospheric hazes and deeper cloud layers is not simple . Some of the more obvious methods are outlined below.

Up-looking instrument viewing diffuse sunlight:

This method involves looking back at the sunlight; the direct sunlight before the probe enters a cloud layer, and the diffuse sunlight once the probe is within and below a cloud layer. The method has one important advantage: it is simple and sure to work. It also will give the downward-streaming radiative flux profile of the atmosphere. However, its utility is probably limited to regions of atmospheric transparency; thus for the methane-rich major planets, to the 5 μm window and the region below 1 μm.

Down-looking instrument viewing thermal flux:

This technique is appropriate where the atmospheric opacity is small enough that a reasonably long path length can be achieved. The deeper, hotter layers in the atmosphere act as a source and the intervening atmosphere as the absorber. Very interesting results with this method might be achieved in Jupiter's 5 μm region.

Instrument viewing an artificial light source (open path):

In its simplest form this would comprise a light source assembly near the entrance aperture of the spectrometer and a retroflector near the top of the probe or suspended below it, providing an open path length of several meters. A more complex form would be multiple path optics with available path lengths of 10-100 m. The major unknown in this method is the potential interference caused by the turbulence as the probe falls through the atmosphere and any aerosols or cloud particles that are encountered.

Instrument viewing an artificial light source (closed path):

If the lower cloud layer on the major planets is very dense and extensive, then an open path would certainly not work, and a closed sampling tube would be required. The aerosols and cloud particles must, of course, be filtered out as the gas is admitted. The method has the additional advantage that there would be no interference from turbulence and the pressure and temperature of the gas sample could be accurately measured. Such a tube, however, greatly adds to the complexity of the experiment; the gas in the tube must be pumped out between samples with a consequent increase in the sampling interval.

Frost deposition of condensible species and cloud particles:

This sampling technique is a fairly radical departure from those described above since spectra of the solid species rather than the gaseous constituents would be obtained. It would consist of a number of cryogenic surfaces held at different temperatures, onto which the various atmospheric constituents would freeze. By cycling the temperature of each surface about a nominal value, the frost or dew point of a particular condensable or cloud constituent could be measured, greatly helping in the interpretation of the various cloud layers. However, since a spectrum of the constituent is also obtained an identification of the cloud particles could be made at the same time.

The method is not restricted to cloud particles. Because H_2 and He have such low freezing points, keeping one surface at ~50K would freeze out all other potential atmospheric constituents so that a complete sampling of the atmosphere would result. All but a few of these would have infrared spectral signatures. In fact, the method has a number of important advantages over the detection of gaseous species in a limited path length. It has been found that all the band intensity is usually concentrated in a Q-branch-like structure with a half width of 20 cm^{-1}, so that a higher detectivity compared to the gaseous state results. Many bands which are forbidden in the gaseous state become allowed for the solid because of interactions in the crystal lattice. Because of the same interactions, some bands in the solid state increase their intensities considerably (e.g. for NH_3, the ν_1, ν_3 complex at ~3.0 μm increases in strength by a factor of 15 going from the gaseous to the solid state). Finally, this method allows the sought-after constituents to be concentrated by collecting them over a fairly long path length (~1 km) in the atmosphere. It is therefore possible that ppb or even better sensitivities might be achieved with this method.

Application Analyses

We have chosen to examine the capabilities of a probe infrared spectrometer in general terms, without regard to the specific technique employed. However, the results which follow are appropriate to gas phase measurements and do not address the capabilities of the frost deposition approach. All of the techniques described above warrant considerably more study than was possible in the preparation of this report.

Table III-2 lists a variety of molecules that have been observed in planetary atmospheres. It gives the positions of the infrared active fundamental bands and their measured band intensities. The table is not complete, but it can be observed that the band strengths of the molecules are typically of the order of several hundred cm^{-1}/cm-amagat so that the table can be thought of as representative of the sensitivity that can be expected.

Two spectral resolutions were considered for these calculations. The low resolution mode was assumed to have a numerical resolving power of 100, or a resolution limit of 20 cm^{-1} at 2000 cm^{-1}. A minimum detectivity of 1% (signal-to-noise ratio of $\geq$ 100) was used and the extent of a band was taken to be about 100 cm^{-1}.

An instrument that would resolve the individual lines in a band was also considered. Of course, in the upper troposphere or above, as high a resolution as possible, subject to the line widths encountered, is desired to maximize the detectivity. However, this region is accessible to remote-sensing instruments so the main working regime of an entry probe spectrometer would be the inaccessible region below the cloud tops. Here the pressures are typically 1 atmosphere or higher, so that the full width of the absorption lines at half intensity (HIW) will be of the order of 0.1-0.2 cm^{-1}. Thus a medium resolution of 20,000 or about 0.1 cm^{-1} at 2000 cm^{-1} suffices. Again assuming a minimum detectivity of 1%, a minimum detectable equivalent width of 0.001 cm^{-1} results. The band intensity would, however, be spread over 20 lines so that an increase of ~10 in sensitivity over the low resolution mode can be achieved.

A conservative estimate of the sensitivity of such instrumentation thus is about 2-30 ppm for the low resolution mode and 0.2-3 ppm for the medium resolution mode. This sensitivity could reasonably easily be increased by a factor of 10 if, for example, the path length were increased to 4 m and the measurements were made at a deeper level in the atmosphere, at a density of 4-5 amagat. This sensitivity compares quite favorably with that achieved by the mass spectrometer and gas chromatograph on the Pioneer-Venus entry probe. For the former the lowest mixing ratio given is 10^{-6} (Hoffman *et al*, 1979) while the smallest detected amount for the latter was Ne with 4 ppm ±100% (Oyama *et al*., 1979).

Critical Hardware Needs

We recommend that a study be initiated to define the required characteristics of an entry probe infrared spectrometer. Since a variety of measurement techniques may be used, a detailed intercomparison of their feasibility should be undertaken.

Evaluation Summary

An infrared spectrometer appears to offer unique benefits for entry probe science. As a complement to the standard mass spectrometer and gas chromatograph, the three together could provide data not otherwise available.

Table III-2. Sensitivity estimate of low-to-medium resolution entry-probe spectrometer

Molecule and Band Designation		Band Origin cm^{-1}	Band Strength $\frac{cm^{-1}}{cm\text{-}amagat}$	Low Resolution Model[(a)] Detection limit[(b)] m-amagat	Low Resolution Model[(a)] Detection limit[(b)] mixing ratio[(c)] ppm	Medium Resolution Mode[(d)] mixing ratio[(e)] ppm
CH_4	ν_4	1306	158			
	ν_3	3019	327	30.6	15.3	1.5
NH_3	ν_2	950	732	13.6	6.8	0.7
	ν_1	3337	30			
	ν_3	3344	20			
H_2O	ν_2	1595	285	35.0	17.5	1.7
	ν_1	3657	9.8			
	ν_3	3756	215			
CO_2	ν_2	667	222	3.9	1.9	0.2
	ν_3	2349	2580			
CO	1-0	2143	261	38.0	19.0	1.9
N_2O	ν_2	589	32			
	ν_1	1285	267			
	ν_3	2224	1534	6.5	3.3	0.3
SO_2	ν_2	518	123			
	ν_1	1158	104			
	ν_3	1362	864	11.6	5.8	0.6
GeH_4	ν_4	819	1175			
	ν_3	2114	1373	7.3	3.6	0.4

(a) Assuming a resolution of 100 (20 cm^{-1}) and a sensitivity of 1%

(b) Assuming a minimum detectable equivalent width of 1 cm^{-1}

(c) With 1 m path length at a density of 2 amagat

(d) Assuming a resolution of 20000 (0.1 cm^{-1}) and a sensitivity of 1%

(e) Assuming that the band is spread over 20 lines, and a minimum detectable equivalent width of 0.001 cm^{-1}

III - 8. POLARIMETER

Measurements of the polarization of sunlight scattered from cloudy planetary atmospheres can yield information concerning the size, shape, index of refraction, and vertical and horizontal distribution of the scatterers. (See Chapter I regarding cloud macro- and microstructure.) The measurements should be repeated over a range of phase angles, scattering geometries and wavelengths to be most effective. The useful wavelength range for polarization measurements is generally limited to that dominated by reflected sunlight because thermally emitted radiation is expected to be essentially unpolarized. Even when the escaping thermal radiation is viewed through a high-altitude thin polarizing cloud, the wide range of directions of travel of the photons incident on the bottom of the cloud would be expected largely to depolarize the observed radiation.

Analysis of ground-based polarimetry of Venus has led to the identification of sulfuric acid as the principal component of the Venus clouds, and the determination of the size of the cloud particles. For other planets, the limited range of phase angles available from the Earth requires measurements from flyby or orbiter missions. To date, polarization measurements of Jupiter, Saturn, and Titan have been made by the Pioneer 10 and 11 missions, and extensive measurements of Venus have been made from the Pioneer Venus orbiter. While the analysis of polarization data tends to be tedious, the data returned from these space missions has been of high quality and will be extremely useful.

Instrument Specifications

The current state-of-the-art for space polarimeters is perhaps best represented by the Galileo Photopolarimeter Radiometer (PPR). This instrument uses a rotating half wave plate in front of a Wollaston prism to measure the magnitude and direction of polarization in three narrow continuum bands at 410, 678, and 945 nm. In addition, the instrument measures intensity alone at seven other narrow bands from 600-900 nm in gaseous absorption regions of various strengths. The instrument also makes radiometric measurements in five narrow thermal channels and two broad channels -- solar only ($\lambda < 4\ \mu m$) and solar plus thermal. A variety of internal and external lamps, calibration targets, and a view of space provide photometric and radiometric calibration.

Details of the Galileo PPR telescope and detectors are:

Collector: 10 cm diameter
Detectors: Silicon photodiodes
Lithium tantalate pyroelectric

Applications Analyses

In view of the extensive experience in building and flying polarimeters, their design appears to be rather well-developed compared with some other instruments. For example, the PPR is a direct outgrowth of the Pioneer 10/11 and Pioneer Venus polarimeters.

Critical Hardware Needs

None

Evaluation Summary

It is the opinion of this working group that the Galileo PPR represents a well-refined instrument design which can serve as an adequate base for future missions.

III - 9. NET FLUX RADIOMETER

A net flux radiometer is a probe instrument for the measurement of the net thermal radiative flux and the absorption of solar energy in a vertical path through an atmosphere. A number of measurement techniques are included in this category; the objective of each depending upon which of the components of the radiation field (thermal, solar or both) is to be measured. The Pioneer Venus mission included three such instruments in the probe instrument complement: a solar flux radiometer (Tomasko et al, 1980) having three spectral channels with five narrow fields-of-view at different zenith angles; an infrared radiometer (Boese, et al 1980) using six spectral channels in two switchable fields-of-view; and a net flux plate (Suomi et al, 1980) using a rotatable differential thermopile ($\Delta\lambda = \sim 0.35$ μm to > 100 μm). These three instruments measured the vertical profile of absorption of solar energy, the net thermal radiative flux profile and the heat balance as a function of altitude in the Venus atmosphere. Measurements of the solar and thermal flux profiles of Jupiter are planned for the Galileo mission.

Instrument Specification

The Pioneer Venus probe flux radiometers are used here to illustrate the capabilities of this class of instrument. The results of the attempt to measure the radiative flux profiles in the atmosphere of Venus with these three instruments illustrates at once the value of the measurements and the difficulty of obtaining them.

1) Solar Flux Radiometer

Spectral channels:	0.59 - 0.67 μm (Si detector) 0.4 - 1.0 μm (Si detector) 1.0 - 1.8 μm (Ge detector)
Fields-of-view:	Five narrow fields at different zenith angle feeding separate detectors

2) Infrared Radiometer

Spectral channels:	3-150 μm (all pyroelectric detectors) 4-5 μm 6-7 μm 7-8 μm 8-9 μm 14.5 - 15.5 μm
Fields-of-view:	Common to all detectors alternately viewing at 45° above and below the horizontal.

3) Net Flux Radiometer

Spectral response:	0.35 - >100 μm (flat to 10% - except for 5 μm diamond window feature - using blackened thermopile)

Field of View: Nearly hemispheric in each of two alternating upward and downward views.

In the probe solar flux radiometer separate lenses defined the five narrow fields-of-view. Quartz light pipes carried the radiation to a detector area cooled by phase change material. No chopping or moving parts were used (dark currents are small and measured before release of heat shield).

The infrared radiometer consisted of six filtered pyroelectric detectors which viewed the atmosphere through a common rotating light pipe which alternately directed their fields-of-view to 45° above and below the horizontal. The fields of view extended to less than 12.5° from the nominal direction. Two heated black bodies placed at 90° from the updown viewing positions were occasionally observed for calibration. Noise equivalent inputs ranged from 0.4 to 0.15 watts/m^2 for the six filter-detector combinations.

In the net flux radiometer spectral response was determined by the spectral variations in the transmittance of the diamond windows over the two sides of the flux plate and the absortance of the black flux plate coating. The field of view was almost the entire upper and lower hemispheres. The angular response was approximately proportional to the cosine of the angle to the sensor normal. Responsivity was about 0.4 μV/watt m^{-2}. The entire flux plate was flipped 180° about a horizontal support arm once per second to allow cancellation of the differences in the thermal properties of the two sides of the flux plate.

Applications Analyses

1) Radiative flux profiles in the atmosphere of Venus

The results obtained by the Pioneer Venus probe flux radiometers are surprising and a unified explanation for the observations of all three instruments continues to be elusive.

The solar net flux measurements agreed reasonably well with Soviet measurements and with the independently measured properties of the Venus clouds. Measurement of the upward and downward fluxes were made with reasonable accuracy, but because different detectors were used in the different directions, the accuracy of the net flux depended sensatively on the calibration of the upward and downward detectors relative to each other (possible to 1-2% level). Calibration errors introduced uncertainties in the level of the net flux, but the shape of the net flux profile was shifted in a systematic and known way.

However, the net flux measurements (Suomi et al. 1980, Tomasko et al. 1980) had many completely unexpected properties. The measurements in the lower atmosphere differed by as much as a factor of 3 from place to place on the planet, while the temperature structure was very uniform as had been expected. The thermal fluxes at some locations in the lower atmosphere were measured to be several times larger than the globally averaged solar net flux.

In view of their surprising properties, considerable attention has been given to the possibility that the thermal net flux measurements might be incorrect for some reason. Despite a design that seems well suited to cancelling out bias errors in the net radiation measurements, the fact remains that the measured values on Pioneer Venus were surprisingly large and variable between the three PV small entry probes. Studies of potential sources of instrument errors are still in progress and deserve to be studied carefully.

Difficulties were also encountered in the interpretation of the results from the infrared radiometer. The rotating light pipe of the radiometer viewed the atmosphere through a flat diamond window which was heated to prevent condensation. Unfortunately, it appears that the instrument shifted relative to the window during the descent in such a way that a portion of the window heater introduced thermal radiation which contaminated the net flux measurements below the clouds. The performance of the instrument itself seems to have been nominal.

Critical Hardware Needs

It is important to understand the problem with the Pioneer Venus net flux radiometer measurements, if indeed they had a problem, because instruments of this type provide a very important type of data obtainable in no other way.

At the moment, suggestions that the net flux radiometer may have viewed part of the thermally perturbed atmospheric wake of the probe (Young, 1980) seem plausible and suggest that simple modification of the instrument field of view could prevent the problem on future missions. It seems that the ability to measure separately the solar and thermal parts of the radiation field would also be very useful on future missions.

For solar and thermal flux radiometers for which spectral and angular discrimination is needed, the development of a means of sharing the same detector for all fields-of-view is highly desirable. The most important improvement would be to combine more complete spectral information (useful for composition determination) with the ability to look upward and downward with the same detector.

Evaluation Summary

At this early stage in the development of instruments for measuring radiative flux profiles, support is still needed to understand and overcome the special problems involved in the use of optical instruments for in situ explorations of cloudy planetary atmospheres. Successful instruments will probably require sophisticated chopping techniques along with special methods to keep windows and optical paths clear. The addition of narrow spectral channels can provide valuable additional information on cloud properties as well as illuminating the nature of possible instrumental difficulties. Despite their problems, the Pioneer Venus instruments form a reasonable base for the development of future missions; for example, a direct descendent of the Pioneer Venus probe infrared radiometer is being built for the Galileo mission.

III - 10. TWO-CHANNEL, WIDE-FIELD BOLOMETRIC RADIOMETER

Wide-field bolometers are employed in the measurement of the global energy budgets of the planets. The major design constraints are that the radiometer view the entire disk of the planet, preferably without sensing any other object, such as rings or satellites, and that the spectral response of the "solar" and "thermal" channels be flat, or nearly so. The full spectral sensitivity of the instrument should include the ultraviolet through near infrared portions of the reflected flux solar (typically 0.2 to 5 μm) and the thermal emission component from the planet (typically 5 to 50 μm). The two-channel bolometer approach to global energy budget measurements is optimum from the point of view of simplicity in interpretation of the observations. Other instrument approaches which provide incomplete spectral coverage or those which are not adequately flat in spectral response require substantial theoretical modeling of the radiative characteristics of the planet; this severely limits the accuracy of the results.

Instrument Specifications

We have chosen the example of measuring the radiative balance of Pluto to illustrate instrument design considerations as well as requirements and capabilities of the two-channel, wide-field bolometer. Other planets and most satellites will be brighter in both the thermal and solar parts of the spectrum and so are easier to measure. Less sensitive detectors may be used for other objects, and the design constraints on the optics relaxed.

Collector: 7.8 cm diameter

Detector Figure of Merit:

Thermal channel, $D^* = 3\times10^8$ cm $\mathrm{Hz}^{\frac{1}{2}}\mathrm{W}^{-1}$ thermistor or pyroelectric

Solar channel, $D^* = 10^8$ cm $\mathrm{Hz}^{\frac{1}{2}}\mathrm{W}^{-1}$ (thermopile)
$D^* = 3\times10^8$ cm $\mathrm{Hz}^{\frac{1}{2}}\mathrm{W}^{-1}$ (pyroelectric)

Field of View: whole planet

Thermal Requirements: the instrument and collector must be cooled for low temperature objects.

Applications Analyses

Global energy balance

For the instrument described above, the acceptable and desirable measurement accuracy objectives (see Chapter I) can be met for Pluto - and with proper scaling of the instrument parameters, the objectives for the other planets and satellites are also met. Signal-to-noise ratios for the thermal channel are 100 for all planets; for the solar channel the signal-to-noise ratios are 2000 or 6000 depending on the detector used.

Critical Hardware Needs

Absolute calibration is required for both the thermal and solar radiation channels. This includes ground based calibration against some reference which can be traced to an international standard and inflight calibration to insure that degradation of optics or electronic components does not invalidate measurements. Stability checks might include redundant channels with one of them shuttered, calibration checks of electronics by a precision step at the detector input, and on-board black bodies and lamps for inflight calibration. An example is the calibration scheme for the Earth Radiation Budget (ERB) experiment successfully flown on Nimbus 6 (Hickey and Karoli, 1974; Jacobowitz et al 1979). The desired accuracy for the channels on this instrument ranged from ±0.5 to 1.0% and the desired precision ranged from ±0.2 to 1.0%. The results achieved for the wide-angle channels were 11% too low, and a degradation of some channels as large as 7% per year occurred. It is difficult to achieve design accuracy in practice (see Appendix A, Section XII: Calibration Sources). Therefore, absolute calibration is an area requiring further development in order to meet reliably the accuracies for space-borne radiometer-bolometers desired for study of the global radiative balance.

Evaluation Summary

Measurements of planetary global energy budget may be made with a relatively simple two-channel, wide-field radiometer. An accurate absolute determination of the radiative budget requires absolute calibration for both the thermal and solar radiation channels.

A precise determination of the global energy balance of a planet requires observation coverage at all phase angles for both the day and night sides, including the poles. This makes a high inclination orbiter at a large distance desirable, even essential, for the instrument. While flyby observations can significantly advance our understanding, uncertainties in the phase angle dependence of the radiation field and substantial unobserved portions of the planet severely limit the accuracy of such measurements. Some modeling is necessary for the inner planets to separate the reflected solar and thermal spectra in the wavelength region of overlap.

III - 11. TWO-CHANNEL, NARROW-ANGLE BOLOMETRIC RADIOMETER

Both the wide-field and the narrow-angle bolometric radiometers require detectors sensitive to the same wavelength ranges (see III-10). The major design differences between these two instruments follow from the requirement that the wide-field radiometer view the entire disk of the planet, and the requirement that the narrow-angle instrument view small regions of the disk.

Instrument Specifications

The example of measuring the radiative balance of Pluto has again been chosen to illustrate a severe test of instrument performance characteristics (see III-10). In order to attain the desirable spatial resolution, we have adopted a 50 cm diameter collector for our hypothetical instrument having a field-of-view of 8 milliradians. Since the field of view of the instrument is filled by the body observed, the size of the orbit is not important except to specify the spatial resolution. An orbiting platform is clearly desirable in order that the entire planet be observed and information be gathered at all phase angles.

Collector: 50 cm diameter

Detector figure of merit: $D^* = 3\times10^8$ cm $Hz^{1/2}$ W^{-1} (pyroelectric detector)

Field of View: 1/10 R_{Pluto}

Thermal Requirements: the instrument and collector must be cooled for low temperature objects.

Applications Analyses:

1) Local energy budget

For this experiment we find that the desirable measurement objectives can be met with a relatively simple instrument with the specifications outlined above. This radiometer gives signal-to-noise ratios of 2000 and 3000 for the thermal and solar channels, respectively.

Critical Hardware Needs

Comments on calibration and instrument spectral response found in the description of the two-channel wide-field radiometer also apply here. However, the narrow-angle radiometer has more stringent pointing requirements (0.1°) because of the narrow view angle.

Evaluation Summary

A radiometer specifically designed for radiative budget measurements has significant advantages over general purpose instruments. To the extent that "solar" and "thermal" channels of the device are not spectrally flat or do not cover the full spectral distribution of outgoing energy from the planet, the dependence of the data analysis on modeling is increased.

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CHAPTER IV

CONCLUSIONS AND RECOMMENDED INSTRUMENT DEVELOPMENTS

A. Technical Conclusions

The working group evaluated various strategies for measuring the atmospheric phenomena outlined in Chapter I on various planets and satellites (Chapter III). These studies were designed to allow quantitative comparison of the strategies; they also led to several general technical conclusions:

1. Sounding of the middle and lower stratospheres of the outer planets must be made while viewing through their relatively hot upper stratospheres (the outer planets exhibit strong stratospheric temperature inversions). If these upper levels contribute appreciable opacity in the observed spectral interval, the radiant energy observed may be dominated by flux from the upper stratosphere. In order to sound temperature or composition in the lower stratosphere, an instrument must have spectral resolving power $\lambda/\Delta\lambda \geq 10^6$ in order to select the near wings of the spectral lines.

2. Detailed calculations of the expected signal-to-noise ratio from Uranus and Neptune show that nadir sounding for composition, abundance, and minor constituent temperature sounding on these objects beyond the region where solar reflection is significant is not viable at spectral resolutions necessary to perform detailed atmospheric studies.

Solar occultation experiments offer significant advantages for the investigation of atmospheres above the main cloud deck. Even at the distance of Neptune the Sun subtends 1 arc min, well above the diffraction limit of even modest sized collectors at $\lambda = 20\ \mu m$. Furthermore, the viewing mode is that of a limb sounder, offering excellent height resolution and increased sensitivity to minor constituents because of the very long path lengths. Since it may be expected that the Sun will fill, or nearly fill, the field-of-view of the spectrometer, signal-to-noise ratio is not a problem. We recognize, however, that such an experiment places severe demands on all aspects of the mission and orbiting spacecraft systems.

Infrared surveys of minor constitutents in the atmospheres of the far outer planets should employ solar occultation spectroscopy for the region above the clouds. The flux levels of thermal and IR reflected solar radiation for these bodies do not permit acceptable results for minor constituent detection to be obtained from nadir or limb viewing emission experiments in reasonable integration times. Initial exploration of these atmospheres can be carried out from suitable Earth orbiting instruments.

3. The addition of an infrared spectrometer to the instrument complement of an entry probe can significantly increase understanding of atmospheric and cloud composition and abundance of species. Suitable instrumentation can profile constituents such as water vapor and detect complex molecules with greater certainty than that provided by a gas chromatograph/mass spectrometer alone.

4. Knowledge of local and global radiative budgets is presently limited by the state of on-board radiometric calibration of both the reflected solar flux and emitted thermal flux.

B. Recommended Infrared Techniques for Investigating the Physical Phenomena

Infrared techniques can substantially increase our understanding of the phenomena discussed in Chapter I. The working group's quantitative assessments of various strategies for investigating these phenomena are discussed in Chapter III. We summarize here the techniques felt to be best suited to measure each of these phenomena.

1) Global and Local Radiative Budget

- Bolometric Radiometry
  - Required Developments:
    - More precise absolute calibration

2) Radiative Flux Profiles

- Solar and Thermal Net Flux Radiometers
  - Required Developments:
    - Improved chopping techniques
    - Methods of clearing windows and optical paths
    - Addition of narrow spectral channels
    - Modeling of probe entry dynamics

3) Winds

- Gas Correlation Spectroradiometry (terrestrial planets)
  - Required Developments:
    - Long hold-time gas cells
    - Improved gas monitoring and radiometric calibration
- Imaging in Combination with Cloud Height and Temperature Field Determination (outer planets)
  - Required Developments:
    - One or two dimensional IR arrays
    - Effective coordination of measurement strategies, including cloud height sensor (CCD imaging, photopolarimetry, or radiometry)

4) Temperature and Pressure

- Gas Correlation Spectroradiometer (low pressure regions $\lesssim 40$ mb).
  - Required Developments:
    - Long hold-time coolable gas cells
    - Improved gas monitoring and radiometric calibration
- Intermediate Resolution Spectroradiometer (for Troposphere)
  - Required Development:
    - Coolable, lightweight instrument
    - Imaging capability

5) Transient and Marginal Atmospheres

- Low and High Resolution Spectrometers
- Filter Radiometer

6) Planatary Rotation and Global Atmospheric Activity

- Imaging to $\lambda \lesssim 5$ microns for deep methane band feature tracking in visibly featureless methane-rich atmospheres (Titan, Uranus, and Neptune).
    - Required Developments:
        - One or two dimensional near IR detector arrays

7) Abundance of Stable Constituents

I. Surveys of Unexplored Atmospheres

- Earth Orbital Spectroscopy (for the region above the clouds)
    - Required Developments:
        - Coolable, lightweight spectrometer

- In-Situ Infrared Spectroscopy (below the clouds)
    - Required Developments:
        - Probe-certified hardware
        - Radiation sources
        - Sampling procedure

II. Explored Atmospheres

- Solar Occultation Spectroscopy (for the region above the clouds)
    - Required Developments:
        - On-board processing
        - Large lightweight coolable, movable, optics
        - Pointing stability

- Gas Correlation/Filter Radiometer (Specific constituents: 1 bar to LTE limit; above the clouds
    - Required Developments:
        - Long hold-time coolable gas cells
        - Improved gas monitoring and radiometric calibration
- In-Situ Infrared Spectroscopy (below the clouds)
    - Required Developments:
        - Probe-certified hardware
        - Radiation sources
        - Sampling procedure

8) Vertical, Lateral, and Temporal Variability of Species

- Gas Correlation/Filter Radiometer
    - Required Developments:
        - See abundance of species section

- Imaging Spectrometer
  - Required Developments:
    - Coolable, lightweight instrument
    - Imaging capability

9) Composition of Clouds and Aerosols

- Low-to-Medium Resolution Spectrometer

10) Radiative Properties of Clouds and Aerosols

- Multiple Wavelength Upward & Downward Diffuse Flux Radiometer on Probe
  - Required Developments:
    - Far Infrared Filters

- Imaging Long Wavelength Radiometer
  - Required Developments:
    - Calibration in 50 - 100 μm region
    - Filters

11) Cloud Macrostructure and Microstructure

- Visible/Near IR Photopolarimeter
- Visible and near-IR Imaging for macrostructure
- Entry Probes for vertical structure

12) Non-LTE Phenomena

- Medium-to-High Resolution Spectrometer
- Laser Heterodyne Spectrometer

C. Utilization of Near-Earth Orbital Platforms

Some experiments can be performed better from Earth orbit than from a planetary orbit or flyby. These include initial detection by high-resolution spectroscopy of low abundance atmospheric species and long-term monitoring of the variability of atmospheric composition and thermal structure on the brighter planets. Several Earth orbital platforms are planned which have relevance to infrared planetary investigations. Their full utilization should be part of the planetary exploration program. These platforms are the Infrared Astronomy Satellite (IRAS), the German Infrared Laboratory (GIRL), the Shuttle Infrared Telescope Facility (SIRTF), and the Space Telescope (ST). Appendix D describes each of these platforms and the opportunities and limitations they present for investigating the phenomena discussed above.

D. Recommendations for Atmospheric Infrared Instrument Development Program

For many solar system objects, we have advanced from initial surveys to detailed investigations of atmospheric physics and chemistry. Even for those bodies yet to be visited, prospects are excellent for the development of new strategies which will offer excellent scientific return even with constrained budgets. The working group found that there is no single measurement technique that permits the investigation of more than a few of the significant atmospheric phenomena.

The detailed technology assessments made by the working group (presented in Chapter III and Appendix A) have defined both the optimum strategies for investigating the phenomena and the developments required for their implementation. Some strategies require little development; their omission from the recommended development program indicates that currently available space-qualified hardware can be proposed for these strategies.

A stable long-term instrument development program is required to apply current laboratory techniques to the spaceborne measurements, take advantage of opportunities offered by Earth orbital platforms and atmospheric entry probes, and improve science return from conventional infrared instruments. With such a plan the United States planetary exploration program will be prepared to use fully the powerful infrared spectral regime to bring our knowledge of composition, structure, and dynamics of planetary atmospheres to levels which our experience with Earth has shown are necessary for an understanding of the origin, chemistry and physics of atmospheres.

Instruments for entry probes, flybys, planetary orbiters, and near-Earth facilities are each important parts of a balanced planetary exploration program; thus the order of recommendations does not denote priority. We recommend:

- That support be given for the development of high and ultra-high resolution planetary infrared spectrometers for Earth orbiting telescopes. Spectrometers which resolve pressure broadened lines and spectrometers which resolve Doppler-broadened line cores are required.

- That support be given to the development of gas correlation spectrometers for the study of physical and species-specific chemical properties of planetary atmospheres.

- That support be given for the utilization of infrared detector arrays in low to intermediate spectral resolution cryogenic imaging systems.

- That support be given to the design of a high resolution solar occultation interferometer for survey investigations of the minor and trace components of atmospheres. Such an instrument can provide high sensitivity for the detection of constituents above cloud layers.

- That studies be initiated to define the required characteristics of a probe/in situ planetary infrared spectrometer for detection and measurement of composition as a function of height below cloud level. An instrument of this type would add significantly to the science return from a probe instrument set.

- That studies be initiated to improve substantially the state of the art of on-board radiometric calibration of reflected solar and thermal flux.

APPENDIX A

CRITICAL TECHNOLOGIES

Introduction

We felt that no discussion of infrared instruments would be complete without an investigation of those technologies critical to their development.

The technologies identified are:

I: Detectors
II: Coolers
III: Cryogenic control mechanisms
IV: Lightweight, coolable, optics
V: Thermal control
VI: Contamination control
VII: Optical components
VIII: Lasers
IX: Non-linear optics
X: Frequency shifters
XI: Active optics
XII: Calibration Sources
XIII: On-board data processing
XIV: Pointing

and for each one we have documented the present state-of-the-art and indicated the likely trend of development in the next few years. Each technology, of course, could be (and often has been) the topic of a major report itself. Our discussions are necessarily cursory.

I: Detectors

Detectors are obviously the single most important technology for the infrared; the advance of the field is demonstrably controlled by improvements in detectors.

Detectors have been the subject of innumerable reports over the years. One of the more recent (and therefore most relevant and important) is the study conducted under the auspices of the NASA Ames Research Center on low-background detectors for use on SIRTF (NASA Technical Memorandum 78598, 1979) and all readers are strongly encouraged to obtain a copy. Indeed, within the limits of time and resources available to us, we did not feel that we could improve upon the completeness of this report, at least for discrete-element detectors. The principal conclusion we draw from the report is that for the 1-20 μm region NEP's of 10^{-16} $WHz^{-1/2}$ or better are realistically available and that 10^{-17} may be possible in the very near future. Such performance does, of course, depend critically upon proper control of the background.

It was, however, clear to us that the upcoming technology of detector arrays, especially those with on-chip processing, will be of increasing importance in the future. 1024-element line and area InSb CID arrays are already commercially available and we are aware of at least one attempt to produce a similar HgCdTe array for the 1-5 μm region. Discussion with manufacturers leads us to believe that with a relatively modest (by detector-development-cost standards) injection of funds, hybrid CID and CCD arrays (probably based on existing Si arrays) could be rapidly developed for the entire 1-20 μm region and we wish to add our voice to the general call for such programs to be adequately funded. The infrared community has urgent need to obtain arrays in order to obtain "hands-on" experience with them because it is already evident that the modes of their use and operation are significantly different from traditional discrete-element systems.

II: Coolers

For infrared purposes, two different kinds of coolers are required: a low temperature, low heat-load, cooler for detector systems (which will include detector elements, preamps, final condenser systems, isolation filters and geometric baffles) and a higher temperature, high heat-load, cooler for the remainder of the optical system and for primary thermal isolation of the low-temperature portion. Optical systems can generally operate at rather higher temperature than the detector itself because the detector filtering and baffling and the use of low-emissivity surfaces in the optical system ensures that the instrument background is markedly reduced. Nevertheless, it is not zero and must be carefully considered in any design.

The primary cooler for any spacecraft is the radiative cooler either operating alone or as the final stage of one of the heat transfer systems described below. Acting alone, current radiative coolers can provide temperatures in the range 120 K all the way up to ambient with allowable heat loads of a few milliwatts at the lowest temperature up to several tens of watts at the high end. In development are systems promising temperatures as low as 70K. Radiative coolers are entirely passive (although some very large systems currently in development will require deployment in orbit) and represent a mature technology. Even so, careful design is essential and proper control of the spacecraft pointing and view directions of scan platforms with respect to other spacecraft elements critical. Although the scale, and hence allowable heat load, of such systems will continue to increase, the ultimate lower temperature limits are unlikely to decrease much further.

The use of liquid cryogens, either direct or indirect (*via* Joule-Thompson expanders, for example) is also well-known but is of little current interest because of the success of stored solid cryogen systems (see below). The future may see a revival of interest in them because on very deep space missions lasting several years to decades the ability to produce the cryogen *in situ* on arrival at the target might be a valuable asset. Obviously, a stored solid cryogen system is impracticable for such missions. Candidate gases for *in situ* liquefaction are obviously carbon dioxide, nitrogen, neon, hydrogen and, possibly, helium.

Stored solid cryogen systems are in current active use. Table A1 details some of their performance characteristics with the lower temperature limit being defined by a rather optimistic 0.1 torr ambient pressure. It is optimistic because even with massive space venting the gas can never escape faster than its mean kinetic velocity V_c and more probably at the local speed of sound ($\sim V_c/2$). 1 to 20 torr is more plausible. The data are from Sherman (1978) and liquid ^{4}He is included for comparison

	Temperature, Kelvin		Heat of Sublimation at 0.1 torr	
Cryogen	at 0.1 torr	at triple point	Joules/liter	Joules/Kgm
LHe	---	2.2 (λ point)	3,220 (Vap)	22,200 (Vap)
SH_2	8	13.8	45,600	507,000
SNe	14	24.5	157,000	105,000
SN_2	43	63.1	252,000	268,000
SCO	46	68.1	304,000	295,000
SAr	48	83.9	350,000	205,000
SCH_4	60	90.7	309,000	594,000
SCO_2	125	217.5	962,000	566,000
SNH_3	150	195.4	1,460,000	1,830,000

Table A 1

While these numbers look impressive, even NH_3 could sustain a heat load of 1 W/kgm of cryogen for only 3 weeks at 150 K. For temperatures closer to those needed by infrared detectors (77 K, say), the allowable loads are significantly less. Nevertheless, operational coolers using a favorite combination of NH_3 and CH_4 have been flown in space. One, with a 1 year predicted lifetime and a total mass of 75 Kgm providing 50 mW of cooling at 80 K, flew on the HEAO-B mission in 1979. Evidently, a solid cryogen system for a multi-year mission would be unreasonably massive and their use is likely to be confined to Earth-orbital missions where a refurbishment capability is available.

The most plausible candidates for deep space missions are mechanical refrigerators of one type or another. Several different ones, based on the Stirling cycle, the Vuilleumier cycle and the reverse Brayton cycle (see Sherman (1978) for details) are in development and can achieve 75 K temperatures with several watts of heat load. Multi-stage systems can achieve 10 K temperatures with a few hundred milliwatts load. Unfortunately, despite massive amounts of development money and time, all are plagued by unreliability, poor efficiency (5% at best) and many models are severe sources of vibration. It is by no means certain that these problems are soluble. The future may then lie with the newer technologies of ^{3}He - ^{4}He dilution refrigerators (for very low temperatures) and continuous adiabatic demagnetization (said to cover "all temperatures"). The latter is claimed to be very efficient and simple but is currently hardly more than a laboratory curiousity. Its use in space is evidently some years away.

In summary, then, temperatures down to 70 K are presently available with a variety of techniques. Lower temperatures can be had only for very limited periods. Clearly there is a major technological gap waiting to be filled.

III: Cryogenic Control Mechanisms

Under this heading, we consider mechanical devices only. The potential problem areas are rolling and sliding contacts and differential contraction of materials. There are no general solutions to the problems (which can be very real) but a significant subset was addressed by a SIRTF sub-committee chaired by H. P. Larson that investigated drive mechanisms for an all-cryogenic Fourier Transform Spectrometer (final report Contr. A-48376B, 1978). A recent review by Baker et al (1981) contains brief descriptions of a number of cryogenic FTS systems.

IV: Lightweight, coolable, optics

The ability to cool lightweight optical elements of significant (~ 50 cm, say) size while maintaining a good figure is obviously critical to many current and future missions. The problems up to the 1 m category seem well in hand. However, we are unaware of any activity to develop very large coolable optics although the benefits could be substantial. Although most of the known systems are diffraction limited at reasonably short wavelengths, the spatial resolution from Earth orbit is inadequate for most planetary purposes. Apertures of at least 3 m would be needed for the planets out to Saturn. Beyond Saturn and for satellite and asteroid studies, even larger apertures could usefully be employed (See Chapter 3). Flyby and orbiter systems would, of course, normally employ much smaller apertures.

The characteristics of several known systems are displayed in Table A 2. We encourage the development of systems capable of meeting the desirable requirements laid down in Chapter I.

Table A 2

Project	FOR D.A.R.P.A.	I.R.A.S.	S.I.R.T.F.	G.I.R.L.	SPACELAB II IR TELESCOPE
Diameter (cm)	50	60	85	40	15
Material	Frit-bonded fused silica	Beryllium	Beryllium or fused silica	Zerodur	Aluminium
Operating Temperature (K)	150 (test)	4	8-22	2-5	8
Mass (Kgm)	4.5	13	?	650	690
Optical Quality (Diffraction Limited at μm)	10?	10	5	8	50
Manufacturer	KODAK	PERKIN-ELMER	UNDECIDED	MBB	SAO, U.FA, MSFC

V: Thermal Control

The thermal control of spacecraft and their associated instruments is a well-developed art provided that the temperatures required fall between about 200 and 300 K. Within this range, temperature control to 0.01 K is not difficult and 0.001 K is probably feasible. Better than 0.001 K is beyond the state of the art. Note that these temperatures are relative to an on-board standard; absolute temperature control to better than 0.03 K has not been demonstrated. The matter is of importance for on-board radiance standards, for instance.

Control of elevated temperatures above 400 K (except for the radiance standards just mentioned) is probably of little significance for infrared instrumentation. Control of cryogenic temperatures (< 200 K) is of major importance but the state of the art is quite rudimentary. Massive heat sinking by the use of vent-pumped solid cryogens seems to offer the best stability. For example, around 50 K the slope of the nitrogen vapor pressure curve dT/dP is about 2×10^{-3} deg/millitorr, from which we may infer that a well-vented system should be able to maintain long-term stability to at least this level and to rather better than this over typical observation times. Nevertheless, the general state of the cryogenic control art bears much improvement and we recommend that steps be taken to encourage its development.

Current thermal control techniques fall into 3 distinct categories: Active (Servo-controlled) Systems; Semi-Active and Passive. The accuracy generally declines in the same sequence.

1) Servo-controlled systems operate in the ± 20 to ± 0.01 K range with extension to ± 0.001 K feasible (although ± 0.003 K relative, ± 0.03 K absolute is the best yet demonstrated). They are generally heavy and expensive on power and their overall accuracy is limited by drifts and imperfections in temperature sensors. These, too, bear further development.

   The available technologies are:

   1a) Electrical heaters. These are effective and readily controlled. They are, however, very wasteful of power. Control is ± .01 K or better.

   1b) For temperatures just slightly below ambient (~10 degrees or less), thermo-electric heater/coolers can operate at 50-60% efficiency. Control is ± 0.1 K or better.

   1d) For the range ± 20 to ± 1 K the Fluid Loop has promise. It is identical in concept to an automobile cooling system: a pump circulates fluid through heat exchangers between the heat source and a radiator. Its principal defect is the limited lifetime of existing pumps. Indeed, no space-qualified pumps are yet available.

2) Semi-Active (Open Loop) systems are useful mainly for the dissipation of large heat loads with relatively poor temperature control:

2a) The most common system is the well-known louver (venetian blind) low-emissivity cover of a radiator surface. Controlled by bi-metallic strips, they function only above 273 K (because the strips fail) and have a limited range of about 4:1 in heat input. A typical radiator/louver combination can dissipate 10-40 watts with an area of 0.5 x 0.5 m.

2b) An alternative means of connecting a source to a radiator is the Thermal Switch. Small, bi-metallic strip controlled, mechanical connections can dissipate up to a few watts with ±10 K control. A slightly more elegant, but developmental, thermal switch employs two interleaved, but unconnected, metallic labrynths attached to conducting rods. The region between the labrynths can be filled and emptied with a gas (by a heated molecular sieve, for example) that provides a convective and conductive connection. A 100:1 on-off ratio is claimed for the device.

The Viking Lander employed a massive thermal switch to control the temperature of the RTG's to ± 15 K. Temperature was sensed by a cylinder of gas whose expansion and contraction forced the opening and closing of a mechanical link under great pressure (> 1 kBar). The surfaces of the contacting plates were coated with soft silver so that dust etc. would not cause a failure of the device. High contact pressures are essential for such systems; their efficiency (conductivity vs pressure) has an $e^{1/3}$ characteristic.

3) Passive systems are simply suitable paints, coatings, surface treatments and insulation together with appropriate spacecraft configurations (don't have the radiator pointing at the RTG!) and attitude controls (don't have the radiator pointing at the Sun!). Their control range is only ± 60 K but they are both the first and last lines of defense for the spacecraft.

VI: Contamination Control

Contamination can severely limit the performance of sensitive infrared instruments in two ways. First, the presence of a cloud of emitting and scattering molecules and particles in the field of view of an instrument causes an increase in the background radiation and, more importantly, in the fluctuations of the background on the detectors, resulting in an increase in the system NEP. Second, the molecules and/or particles can be deposited on optical surfaces within the instrument and greatly increase the scattering and absorption of radiation. Both of these problems are greatly exacerbated in the instruments which have cooled optical systems because the sensitivity of such instruments is limited by background fluctuations and because particles and gases will readily condense onto cold optical surfaces. For example, the SIRTF can detect a single 5 μm diameter particle in the field of view at a range of 10 km (Simpson & Witteborn, 1977).

Care must be taken in mission planning and instrument design to avoid impingment of upper atmospheric molecules and dust particles on optical surfaces.

There are numerous sources of the contaminating gases and particles. In low earth orbit, the residual atmosphere itself is significant. Contaminant sources for Space Shuttle operations have been reviewed by Simpson and Witteborn (1977, 1978). These include outgassing from various surfaces, firing of vernier rockets of the attitude control system, venting of water from the fuel cells, cabin leaks, release of dust, dirt, and paint flakes from surfaces, and spallation of particles from the ceramic tiles due to micrometeoroid collisions.

In deep space, the individual sources of contamination will be reduced, but the exposure time will be much longer. Emission from the cloud of contaminants should not be significant on an interplanetary mission, but condensation on cold optical surfaces would be.

A number of strategies are available for reducing contamination. The first is, of course, cleanliness of instrument, spacecraft, and launch vehicle. Contamination control needs to be built into the system from the very beginning. Even where there are certain levels of contamination unavoidably associated with the vehicle, as in the case of the Shuttle, changes in operations can mitigate their effects. These include keeping instruments sealed during the early part of the mission when outgassing is most rapid, scheduling observing periods during periods when no venting of waste occurs, utilizing pointing methods that do not require vernier engine firings, and observing in directions along the negative spacecraft velocity vector.

For cryogenic instruments with long lifetimes, it may be necessary to provide a method of heating the optical surfaces most susceptible to contamination to drive off accumulated contaminants. It is necessary to provide thermal decoupling of the components to be heated and the cryogenic system to avoid overloads and/or coolant waste.

The boil-off from stored cryogens can be used to purge the optical system. For very long missions, the boil-off rate may need to be too low to be effective, but shorter missions could afford to be more profligate with cryogen. With an expenditure of 20 kg for a 28 day mission, SIRTF purges continuously at a pressure of 2×10^{-5} Torr, which produces a mean free path of 20 cm (Simpson & Witteborn, 1977). Thus a molecules entering the telescope undergoes several collisions before reaching the optics and in most cases will be swept back out.

It appears, then, that the technology of contamination control is reasonably well understood and no particular new developments are required. However, great care is required at all stages of instrument design and construction to minimize the effects.

VII: Optical Components

The constraints on optical materials for space instrumentation include low weight, high stiffness, low-thermal expansion and good long-term stability. In addition, the effects of ionizing radiation (such as gamma rays) and irradiation by charged particles on the material must be taken into account. Suitable materials have been found for the optical and ultraviolet spectral regions, and it is likely that no fundamental problems will be encountered in the infrared. Technologies or techniques which may limit the performance of future space instrumentation are listed below:

1. Far-infrared technology. There is a need for the development of good narrow-bandpass far-infrared filters and good beamsplitters for FTS use. In addition, the efficiency of "light pipes" which are used for focussing far-infrared radiation onto the detector could be improved.

2. Active optics. Although these are discussed separately (XI, below), their mention is pertinent here because their use implies certain constraints on the character of the optical elements employed. For example, the use of edge-mounted components can make their use in servo systems difficult because of mechanical resonances in the body of the element. Also falling within this category are tuneable filters, such as mechanically or pressure-scanned Fabry-Perot filters and thermally-scanned bi-refringent filters of the Solc or Lyot type.

VIII. Lasers

The use of lasers to perform sophisticated experiments and feasibility demonstrations from Spacelab has been considered by the NASA Shuttle Lidar Working Group (1979). In addition, NASA and NOAA (National Oceanic and Atmospheric Administration) are examining laser technology to provide global meteorolgical measurements from a long-duration operational spacecraft mission.

At the present time, only two types of lasers have been flight-qualified: the pulsed Nd:YAG and the CO_2 laser. The Nd:YAG laser operates at 1.06 μm in the near infrared, but can produce tunable radiation in the visible and near ultraviolet by nonlinear mixing and pumping of various dyes. The low-pressure CO_2 laser is line-tunable over the 8-12 μm region of the infrared. There is a wide wavelength range, however, from portions of the ultraviolet through the infrared, which cannot be reached with state-of-the-art tunable lasers.

The main NASA support for the development of tunable lasers in the ultraviolet is directed toward the Excimer class, which have the potential for high efficiency of operation in addition to tunability. In the visible, metal halide lasers are being explored under NASA support; and in the infrared, some basic work is being directed toward the development of high-pressure CO_2 lasers and the nonlinear doubling of their frequency to produce radiation in the 4-6 μm region. Most of the work in developing wavelength-tunable lasers is being funded by the Department of Defense (DoD).

The main attributes of lasers for NASA space applications are:

1) High frequency purity - permits small regions of the atmosphere or ground to be sounded from a long distance; permits precise measurements of wind speed via the Doppler shift in return signal; produces very sensitive and specific species measurements remotely.

2) Wavelength tunability - permits adjustments in wavelength to reach and/or scan through characteristic spectral lines of species.

3) Pulsed operation capability - allows range-gated measurements to be made with relatively high spatial resolution, analogous to conventional radar.

4) Efficiency of operation - some present lasers have operating efficiency adequate for short-term space applications - many others do not. This is a major consideration for developing space-qualified lasers.

Because of the importance of the CO_2 laser to global measurements of wind fields in the lower atmosphere, a combined NASA-NOAA team is currently looking into the state-of-the-art of this type of device vis-a-vis the anticipated needs for an operational satellite. One key requirement is that the laser be capable of providing 10^9 shots of laser energy during its lifetime; this is two orders of magnitude longer than any current device has demonstrated. Similar analyses will be made during the next few years on other types of lasers as the need to operate them on NASA spacecraft becomes more evident. NASA is kept aware of developments in DoD-supported work through its membership in the Advisory Group on Electron Devices - Working Group D (Lasers), operated by the Office of the Under Secretary of Defense, Research and Engineering.

IX. Nonlinear Optics

The term nonlinear optics is applied to devices which use nonlinear optical effects to modify electromagnetic radiation in the optical and infrared regions of the spectrum. Examples of such devices are modulators, mixers, frequency doublers, and frequency shifters.

The use of lithium niobate as a nonlinear element in various mixing and OPO (Optical Parametric Oscillator) configurations is a fairly well developed technology which is used for various commercial products. The $LiNbO_3$ crystals are commonly used with pulsed Nd:YAG pump lasers. The long wavelength cutoff for lithium niobate is 4 μm. For longer wavelength generation, other nonlinear materials must be used, which suffer from various drawbacks, including low damage thresholds, difficulty of growing high quality crystals, or small nonlinear coefficients.

A new technology which is being heavily supported by Department of Energy applications is the use of high pressure gas cells to Raman shift various pump frequencies toward longer wavelengths. The gases H_2, O_2, CH_4, and N_2 are being used in ongoing experiments at Los Alamos Scientic Labs., Lawrence Livermore, and Exxon New Jersey Laboratories, in order to generate wavelengths for isotope separation. When used with suitable pump sources in the near infrared, or with CO_2 laser sources, this technique shows promise for the generation of tunable pulsed radiation in the middle (2-15 μm) infrared. This technology warrants further development.

Electro-optic and acousto-optic modulators for use with infrared lasers have received comparatively little development support. One major application of modulators for CO_2 lasers is in optical communication systems, which were proposed to NASA for development around 1970. Support for this activity failed to materialize; consequently, there has been little progress in development of modulators for space applications. The development of modulators which operate in the rf region up to several hundred MHz appears feasible and warrant development for use in a variety of remote sensing tasks.

X: Frequency Translation

Frequency shifters are devices that interact with a beam of light to produce a change in frequency or wavelength by controllable amounts.

The technique of frequency translation has important potential for use in:

1) Passive infrared devices for the direct measurement of atmospheric winds by the technique of gas correlation.

2) Correlation spectrometers in determining trace amounts of atmospheric gaseous species and temperature.

3) Tuning of laser radiation for high resolution spectroscopy by conventional methods or by heterodyne methods using high speed photomixers.

4) Communication between rapidly moving stations (satellites) where coherent detection methods are anticipated.

5) Measurement and/or removal of instrument-target radial velocity effects (i.e. Doppler shifts)

Several methods exist for shifting radiation in frequency. The most useful in the infrared are: 1) Doppler shifting in radiation by scattering it from moving acoustical waves in an appropriate transparent solid and 2) selective choice of sidebands of an appropriately modulated wave. The latter can be accomplished using the electro-optic effect.

The use of the linear electro-optic effect has been demonstrated in various laboratories to produce shifts of laser radiation. For example, Carter and Haus at MIT Lincoln Lab (1979) produces a shift of 10.6 μm CO_2 laser radiation by 17 GHz with a 67% efficiency on a pulsed basis; Campbell and Steier at USC (1971) produced a 110 MHz shift of 0.633 μm He-Ne laser radiation with practically 100% efficiency on a CW basis. The R&D effort in Electro-optical frequency translation has, evidently, proceeded at a low level in recent times since Acousto-optical devices are more attractive for most laser applications.

The electro-optic effect may also be used to phase modulate (equivalent to frequency modulation) optical radiation. This type of modulation produces a large number of sidebands (with generally rapidly decreasing intensity as the order increases) on both sides of the carrier. With a proper choice of operating parameters the carrier may be suppressed. In spite of the large number of sidebands it is possible to put as much as 50% of the energy into the first upper and lower sidebands; for some applications the large number of sidebands is not relevant.

At present, acousto-optic devices are most commonly used for laser beam detectors, tunable narrow band filters, and optical modulators as well as for frequency shifting. The range of frequency shift possible generally increases as the optical wavelength decreases, partly because better opto-acoustic materials are available and partly because less acoustic power is required for efficient diffraction. In the thermal IR frequency shifts approaching 100 MHz are possible with efficiencies of ~50% for one polarization (100 MHz is the Doppler shift corresponding to 1000 m/sec at 10 μm). Electro-optic devices are used for Kerr cells and a full range of technology exists for these from the visible to the IR. In general, the translation frequency range increases and the power required decreases as the optical wavelength decreases.

Acousto-optic frequency shifting requires development of new materials (for example Te) in order to achieve the substantial frequency shifting required for two-component passive wind sensing. Electro-optic devices are not traditionally operated as frequency shifters and it is not clear what difficulties will be encountered in this development. However, it is clear that crystals with larger physical dimensions will be advantageous. Appropriate RF circuitry for generating the high intensity rotating electric field must also be developed.

XI: Active Optics

"Active optics" are that class of optical elements which are able to change their shape so as to produce a more desirable wavefront or a sharper image. By using active optics one can, for example, hope to achieve diffraction limited performance from a telescope which was perhaps manufactured to less stringent tolerances than finally desired, or a telescope which is subject to thermal variations or gravity unweighting which would tend to distort the mirror (Hardy 1978). "Active optics" also imply relatively slow changes, as distinguished from adaptive optics, which generally involve rapid changes such as are found when trying to compensate in real time for atmospheric seeing effects.

Active optics could be of enormous utility to all types of remote sensing investigations, including ground-based astronomy. A prime example is the Space Telescope, which has 24 piston-type actuators on the back side of the primary mirror. By selectively distorting the mirror with these actuators and carefully monitoring the image quality in the focal plane, it is expected that it will be possible to remove the figure-destroying effects of gravity unweighting, thermal gradients, etc. Note that this type of control over the optical wavefront also means that other distortions from subsequent optical elements can in principle be reduced, (for example a warp in the secondary mirror).

Active optics will be critically important in a large collector, such as a 10-30 meters diffraction limited (beyond 30 μm) telescope (Murphy *et al*, 1980). Further potential applications include a very large space telescope for the optical (Nein and Warner 1980), coherent telescope arrays for space astronomy (Traub and Gursky, 1980), and enormous telescopes (Korsch 1980). All of these and ultraviolet instruments have potential for planetary imaging down to the arc millisecond level. There are, in addition, clear potential applications to orbiter and flyby missions, especially those wherein instrument lifetimes of decades in remote environments make conventional construction procedures difficult.

Modest levels of support for planetary experiments using active optics could be fruitful because of a great deal of money has already been spent in this area by the military (DARPA) and we encourage the tapping of this technology base.

XII: Calibration Sources

The requirements on radiometric measurements, necessary for the determination of global and local radiative balances for the planets, severely strain current measurement capabilities in many cases. The requirements laid down in Chapter I for such measurements demand an accuracy of 0.5% or better with 0.2% precision. Current high temperature (> 400 K) radiometric calibration sources can provide radiant fluxes known in the range 0.1 - 1% under carefully controlled laboratory conditions. Below 400 K, in the range applicable to the outer planets, good laboratory standards are of the cryogenic type and in principle can provide accuracies of about 1%. Transfer to and maintenance of high radiometric accuracy in sources satisfactory for operation in the spacecraft environment which are compatible with future measurement requirements are very difficult and are, to some extent, unsolved problems. In addition, characterization of the long term effects of the space environment on blackbody calibration sources and other optical components is not well known. The variety of sources presently used for on board calibration of optical instrumentation includes blackbodies, photometric sources such as the tungsten halide lamp and celestial sources. Design and/or radiometric measurement of these types of sources need to be refined in order to provide the accuracy required. Some of these are listed below:

1. Methods for measuring the surface temperature of blackbody sources on spacecraft.

2. Better characterization of the emissivity of the sources as a function of temperature, wavelength, angle of radiation, surface roughness and type of "blackening" agent.

3. Improved blackbody designs suitable for use on spacecraft.

4. Determination of the long term stability and surface integrity of these sources in the space environment.

5. Broader coverage of the spectrum (0.2 to 500 microns).

6. Calibration sources should be available over the range of temperatures approximating the source of radiation under measurement. For example, low temperature sources may well fit the distribution for the thermal radiation from a planetary source, however, development of a source having the solar distribution is needed for measurements of the reflected sunlight.

7. Explore the use of new absolute radiometric devices such as the self-calibrated silicon photodiodes describes by Geist (1980). These absolute radiometers are capable of better than 0.04% accuracy in the spectral range from 400 to 800 nm and appear to be robust enough for the space environment. Techniques applied to germanium detectors may extend this type of absolute radiometry into the infrared. These devices might be used directly to calibrate sources on board spacecraft and thus relax some of the above requirements.

8. Precision broadband spectroradiometric calibration of celestial sources from Earth orbit.

XIII: On-Board Data Processing

On-board data processing involves the processing of the scientific and engineering output from an instrument, the control of the observation sequences and of the spacecraft itself. Three aspects are of particular importance: microprocessor CPU's, memory devices and software.

a) Microprocessors

Advanced 8-bit microprocessors with sub-microsecond instruction execution times are in current production and several first generation 16-bit devices are available. Within a year or so, a number of 32 bit devices are expected. These will support massive memories, major amounts of I/O and hardware floating point arithmetic. Their capabilities will not fall far short of major mainframe systems now in common use. Most systems can be radiation-hardened at some sacrifice in speed and all can be flight-qualified without undue difficulty. The source of these advances is the considerable effort being put into Very Large Scale Integration (VLSI) by all manufacturers throughout the world. Confident predictions are being made of devices that will contain 10^6 gates on a single chip and it should be borne in mind that most electronic industry predictions have been conservative.

For dedicated hardware (i.e. not reprogrammable in flight) needing extreme speed and unlimited precision, bit-slice logic is already available that uses a high degree of microprogramming and parallel processing at some cost in power consumption (1/4 - 1/2 Watt per bit of precision)

b) Memory Devices

In current production are 16 Kbyte CMOS and 64 Kbyte TTL semiconductor (volatile) memories and 1 M byte bubble (non-volatile) memories. Available soon will be CCD memories. Bubble and CCD memories are slower than semiconductors (10 - 20 msec for bubble memories) but are very compact. In any case, the likelihood is that large semiconductor memories will be integrated into the microprocessors themselves so only mass-storage devices will need to be external to the CPU.

For fixed memories, the traditional type of fusible-link programming is already in the process of being displaced by the Programmable Logic Array (PLA) which offers greater speed and better manufacturing control.

For truly mass storage, the tape recorder seems still to be the device of choice for the foreseeable future. For some reason, there appears to be no particular effort being made to introduce disks for flight use although they would clearly be useful for storage in the 1 - 100 Mbyte range.

c) Software

It is estimated that software costs are 60-80% of the total cost of any computer system and that, at present rates, the price of software is $10 per written line (IEEE SPECTRUM 17, 32 (1980)). Since hardware (including circuit design, construction and debugging) is relatively cheap it follows that increasing emphasis is being placed both on "smarter" hardware and easier software. There is little doubt that high-level languages are replacing assembly languages even for tasks such as instrument and process control that have traditionally used machine code and assembly language. Furthermore, hardware compilers are now in development, further reducing the need for assemblers. The high-level language that appears to dominate the microprocessor field is PASCAL and increasing numbers of manufacturers are including it in their repertoire. DOD, on the other hand, prefers ADA and a new language PEARL also seems to have claimed adherents. The more traditional languages such as FORTRAN and ALGOL remain available but neither is especially suited to process control. FORTH, a language devised for just such purposes, is becoming very unpopular because of poor legibility.

Because the power of on-board data processing will shortly rival the mainframe systems now being used by investigators for engineering and science analysis and the subsequent reduction, modelling and synthesis common to any scientific investigation, it seems clear that a good deal of the initial effort of raw analysis of spacecraft data might well be performed on-board. From an engineering standpoint, the monitoring of voltages, temperatures, frequencies, accelerations, etc. and the corrective actions to be made could well be done in real time with a consequent reduction in transmitted data volume. For the scientist, the application of orbit timing, geometry and calibration sequences could be done in flight with a significant saving in the time and effort needed to get to the real activity of doing science. The "data analysis" phase of current missions is often far more extensive than the "science analysis" and, in an era of shrinking budgets, the "on-board" approach offers substantial cost benefits. From a scientific standpoint, the ability to respond in real time to rapidly-changing events will be essential to investigate some of the phenomena discussed in the main report: in the outer solar system the light-time to Earth can exceed 4 hours (Neptune, one way).

XIV: Pointing

The pointing requirements for a particular atmospheric measurement are dependent on the observation geometry (nadir, limb), distance to the object from the instrument, the velocity of the spacecraft relative to the object, measurement accuracy and dwell time requirements, and the vertical structure of the atmosphere of interest.

For planetary observations from near earth orbit, the telescope pointing requirement for a facility such as SIRTF of $\pm$ 1 arc sec (2.8×10^{-4} rad) accuracy and stability of 0.25 arc sec for a diffraction limit of 5 μm are within the capabilities of the current performance goals of the Shuttle Instrument Pointing System. This system employs a star tracker.

For planetary flyby or orbiter missions the requirements for pointing are primarily dependent on the spatial resolution, the field of view registration required and on the instrument dwell time. Pointing accuracy of 0.1° for nadir views provides spatial position accuracy to 1.7 km per 1000 km of distance from the instrument to the object. Recent spacecraft (such as Voyager and Pioneer Venus) have achieved accuracies of $\sim 0.3°$.

The situation is more complex for atmospheric limb measurements. In the case of passive measurements of the zonal and meridional winds of the terrestrial planets with typical spacecraft orbital geometries the allowable pointing uncertainty is ~ 0.01° for a 1 m/s velocity uncertainty. However, limitations in pointing accuracy can often be offset by knowledge of accurate pointing information.

Limb measurements of vertical temperature structure and constituent abundances require good pointing accuracies. For accurate measurements of atmospheric layer temperature (± 1K) and composition (±10% with 1/2 scale height resolution in terrestrial and outer planet atmospheres the pointing uncertainty requirement is $0.2 - 0.01^{\circ}$ in the vertical plane. If an instrument provides its own pointing reference, from a pressure measurement or by locating the planet horizon, the pointing requirement is replaced by a platform stability requirement; this, in turn is dependent on the time taken for a measurement sequence.

Infrared horizon sensors are typically used for nadir-pointing Earth orbiters to provide two-axis attitude information. The VOIR spacecraft, now in its design phase, will use horizon sensors to achieve an attitude control of 0.5° with respect to the local nadir. Infrared sensors of this type are not suitable for accurate attitude control in exploration missions since detailed information on the vertical structure of the planet's atmosphere and clouds is required in the sensor design.

Recent developments in star trackers show considerable promise for high accuracy pointing systems. Large CCD imaging arrays (800 by 800 elements) can be used to measure precise star images coordinates wherever the image falls within the field of view. Techniques are being developed for tracking moving images electrically for use on spacecraft with no axis fixed in inertial space, a previous limitation of star trackers. Pointing accuracies of 3×10^{-4} (3σ) and stabilities of 3×10^{-5} rms are expected with these devices. Development is, however, still required in the following areas: silicon CCD arrays; micro-processors for image processing and star catalogue correlations; survivability of all system components (sensor, thrusters, bearings, electronics, gyros) in long duration missions.

Spin-stabilized spacecraft are currently favored over 3-axis-stabilization for long duration missions because of their proven reliability and minimal complexity. Three-axis systems require continuous operation, and they require extensive self-test and automatic reconfiguration to overcome failures. The dual-spin approach is also a good candidate for this class mission and will be implemented for the Solar Polar Mission. However, there are difficulties with despin-motor bearing life for 8-14 year missions, and configuration problems with large high-gain antennas.

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APPENDIX B

APPLICABILITY OF ATMOSPHERIC INFRARED INSTRUMENTATION TO SURFACE SCIENCE

Several of the atmospheric instrument classes which are recommended for development may be able to address questions relevant to surface science. While attempting to design an instrument to perform several functions may in many cases be impractical, it is sometimes possible to extend an instrument's design to permit broad use. In order to allow early considerations of multiple use in the design of atmospheric instrumentation we present here a brief synopsis of some of the relevant characteristics of surface materials.

Spectral features of minerals and simple condensates are usually observed in the solar reflectance region. These absorptions are generally rather broad crystal field or charge exchange transitions (e.g., the water ice spectrum of Figure B-1). No quantitative theories of mineral absorptions have appeared which allow the generation of a synthetic spectrum; the primary means of identification of features is matching of the position, equivalent width, and absolute albedo of the spectral signature with laboratory reflectance data. The presence of gentle slopes of the continuum in the spectrum is also diagnostic for certain minerals and condensates. Since surface spectral features tend to be more ambiguous than atmospheric molecular absorptions, several absorptions and slopes over a range of wavelength are generally used for identification.

Figure B-2 shows the importance of absolute albedo and continuum slope information for identification. Band locations and continuum slopes in the solar reflection regime for several simple condensates and naturally occurring minerals are summarized in Figure B-3. Characteristics of an instrument which would allow it to make contributions to mineral and condensate identification include broad spectral coverage, encompassing a large portion of the solar reflectance regime down to ~ 0.4 microns; absolute albedo capability; and ability accurately to measure gentle continuum slopes. Imaging capability combined with spectral measurements increases the chances for detection of isolated minerals and allows mapping of geological units.

Further information about surface and interior properties is available from long-wavelength broad-band radiometric data. Measurements of the body's thermal inertia (as measured through a day/night or eclipse transition) and emissivity provide important constraints on the composition and layering of surface material and, occasionally, on internal heat reservoirs. For the solid bodies of the outer solar system several channels from the near infrared to the 40 micron regime are required to define the blackbody characteristics. Absolute radiometric brightness has also been utilized to estimate the size of unresolvable small bodies; sensitive measurements of this type from Earth orbit will be useful in studying the objects discovered in the Infrared Astronomy Satellite's asteroid survey.

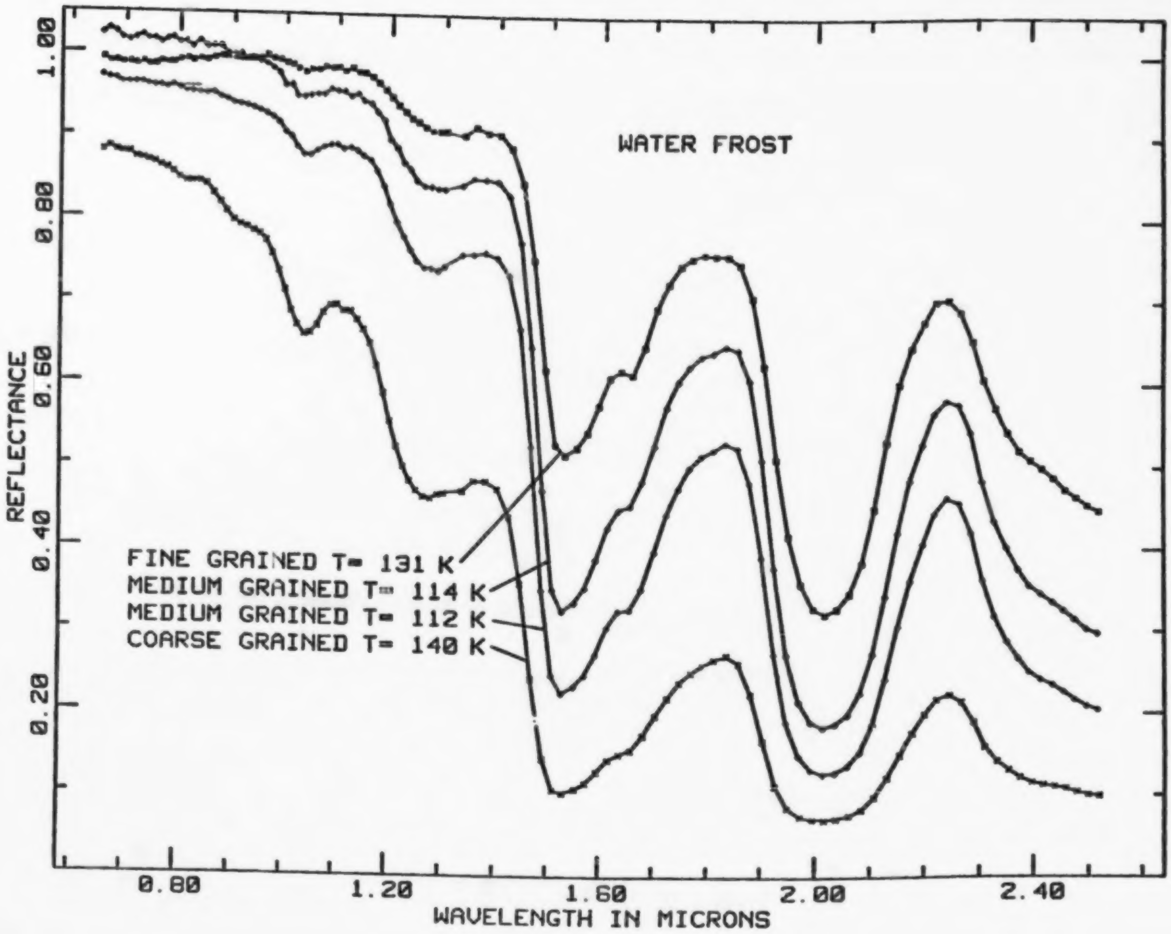


Fig. B-1 The spectral reflectance of pure water frost for several grain sizes, showing the broad absorptions which characterize many condensate and mineral spectra. Courtesy of R. N. Clark.

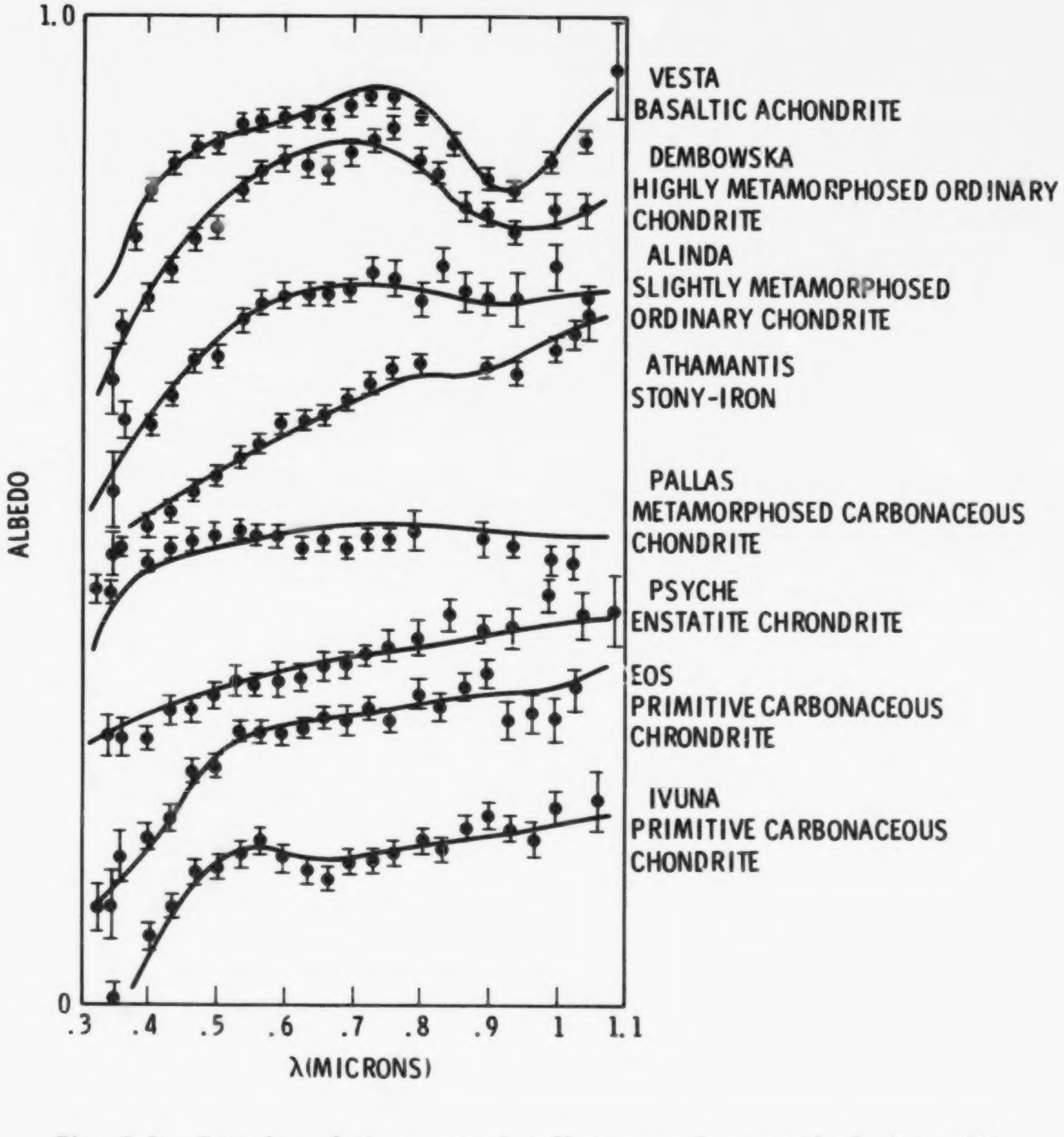


Fig. B-2. Examples of the spectral reflectance of asteroids (points with error bars) compared to various meteorite samples (curves), illustrating the importance of absolute albedo data in ascertaining surface analogs. From Matson et al., Proc. Lunar Sci. Conf. 7th (1976) p. 3613.

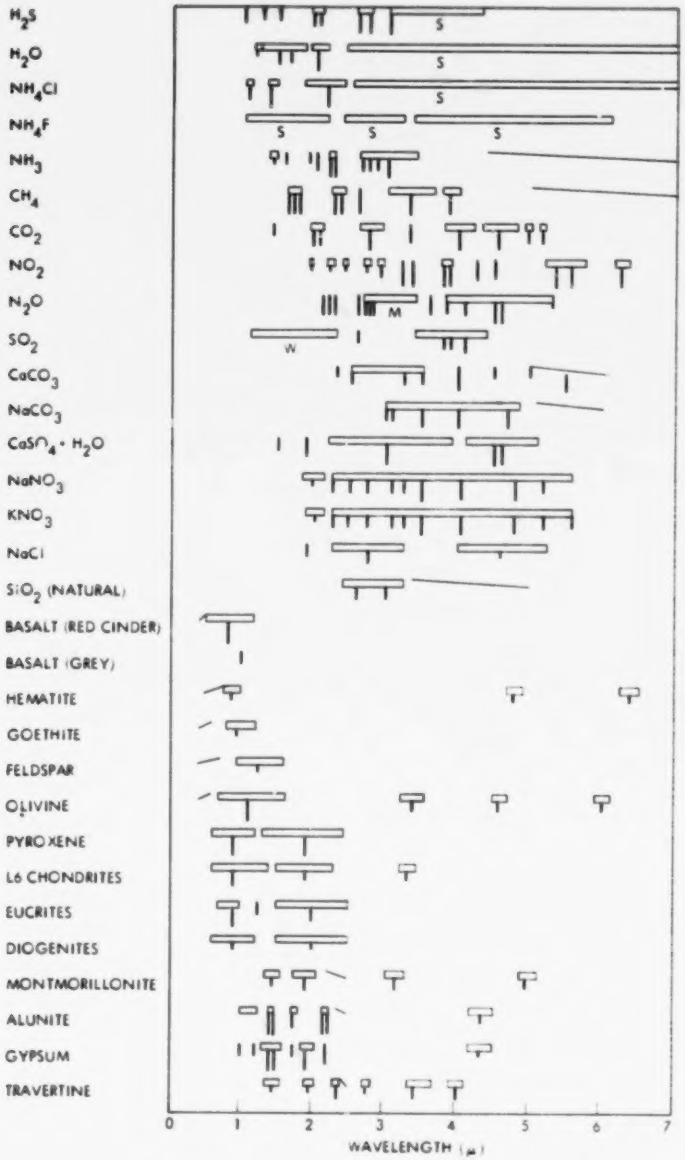


Fig. B-3 Mineralogical Infrared Spectral Reflectance Features of Planetary Interest. This figure summarizes the near-infrared band locations and strengths for some simple condensates and naturally occuring minerals as observed in reflectance. Boxes indicate the width of broad bands and vertical lines indicate the approximate positions of sharper absorption features, with strengths indicated by their lengths. Broad slopes are indicated by slanted lines. The strength of broad absorption bands are indicated by letters (S=strong, M=medium, W=weak). Some multiplet structure is unresolved in this summary.

APPENDIX C

SUPPORTING STUDIES IN DATA ANALYSIS AND NUMERICAL MODELING

The successful application of infrared measurement techniques to the study of planetary atmospheres depends critically on supporting theoretical studies and data analysis techniques, including:

- Numerical models of planetary atmospheres and of radiative transfer in planetary atmospheres for instrument design and performance estimates.
- Retrieval techniques for data analysis.
- Laboratory spectroscopy of atmospheric constituents in gas, liquid and solid phases.
- Analysis of existing ground-based and spacecraft observational data.

Major advances are required in each of these areas in order to realize the maximum scientific return from future flight experiments. It is abundantly clear from previous experiments that the success of an instrument is highly dependent on these numerical tools and data sets. This fact was repeatedly demonstrated in the study by the working group of past and future instruments for the study of atmospheric phenomena.

A particularly urgent need exists for the development of analysis techniques for the remote sensing of temperature (or species abundances) in the presence of clouds and aerosols. The limitation of retrieval techniques to clear atmosphere conditions is generally unacceptable. The clouds of Venus, dust in the atmosphere of Mars, and the hazes and clouds of Jupiter, Saturn, Titan and the far outer planets inhibit the success of current retrieval techniques. Since the properties of the clouds and aerosols are unknown there are many solutions which are acceptable to a retrieval scheme. Decoupling the cloud structure from the temperature structure (or species abundance profile) effects in the measurements is most difficult. A number of approaches to this problem warrant further work, including the judicious use of multispectral data and multiple zenith angle coverage in the simultaneous retrieval of temperature and cloud properties.

Temperature sounding of the outer planets is difficult for a number of additional reasons. The use of H_2 and CH_4 for temperature sounding has been demonstrated in the tropospheres of Jupiter and Saturn. However, the possible non-homogeneous distribution of CH_4 in the atmospheres of Uranus and Neptune presents new problems which have yet to be addressed. The sounding of temperature and species abundances in the stratospheres of the outer planets presents severe difficulty for conventional measurement and retrieval techniques--a consequence of the large increase in temperature with height above the tropopause in these atmospheres. Techniques for temperature sounding in Titan's atmosphere from the surface to limb require development.

Models of the extreme upper atmospheres of the outer planets are necessary to describe the non-LTE radiative transfer functions and to identify the key photo-chemical species and processes. The refinement of models for upper and lower atmospheres of the far outer planets is essential for the optimum design of flight experiments.

The need for a comprehensive program of laboratory spectroscopy has already been argued by the Conference on Molecular Spectroscopy (March, 1980, Annapolis, Md.) and the Infrared Experiments Working Group gives its wholehearted support to such a program. These laboratory studies, coupled with a vigorous pursuit of data analysis programs for previous flight and ground-based planetary data, will do much to improve the science return from future missions.

APPENDIX D

DESCRIPTION OF PLANNED EARTH ORBITAL PLATFORMS

Several low Earth orbital platforms are planned which can be used for infrared planetary investigations. Their full utilization should be part of the planetary exploration program. These platforms are the Infrared Astronomy Satellite (IRAS), Space Telescope (ST), the Shuttle Infrared Telescope Facility (SIRTF), the German Infrared Laboratory (GIRL), and the Shuttle Experiments of Opportunity Program (EOP). In this Appendix we describe briefly each of these platforms and the opportunities and limitations they present for investigating the phenomena discussed in Chapter I.

Table D-1 summarizes some properties of these platforms, and the instruments presently defined for them. Further information is provided for each platform at the conclusion of this Appendix. Figure D-1 shows the spatial resolution of the platforms for various planets.

We have assessed the ability of these platforms to meet the acceptable and desirable criteria for measuring the atmospheric phenomena outline in Chapter I. The Infrared Astronomy Satellite (IRAS) cannot greatly assist planetary atmospheres questions (although it will play a role in detection and photometry of asteroids). The German Infrared Laboratory (GIRL) can make major contributions to detection of atmospheres and detection and abundance of species on certain planets. It is presently not funded for planetary work, and a strong U. S. participation in funding a flight for this purpose may be extremely cost effective. The Shuttle Infrared Telescope Facility offers the possibility of high sensitivity observations of remote solar system objects. Photometric instruments in its focal plane may be used to study radiative balance in outer solar system objects. SIRTF's full potential for the study of planetary atmospheres cannot be achieved unless a high resolution spectrometer is included in the focal plane. Although not presently carrying any IR instruments, the Space Telescope could meet acceptable requirements for measurement of some atmospheric phenomena if suitable instrumentation and time were available.

Presently planned Earth orbital facilities can meet the desirable criteria for measurements of atmospheric phenomena for 2 phenomena: detection of atmospheres (GIRL, and ST) and atmospheric rotation (ST).

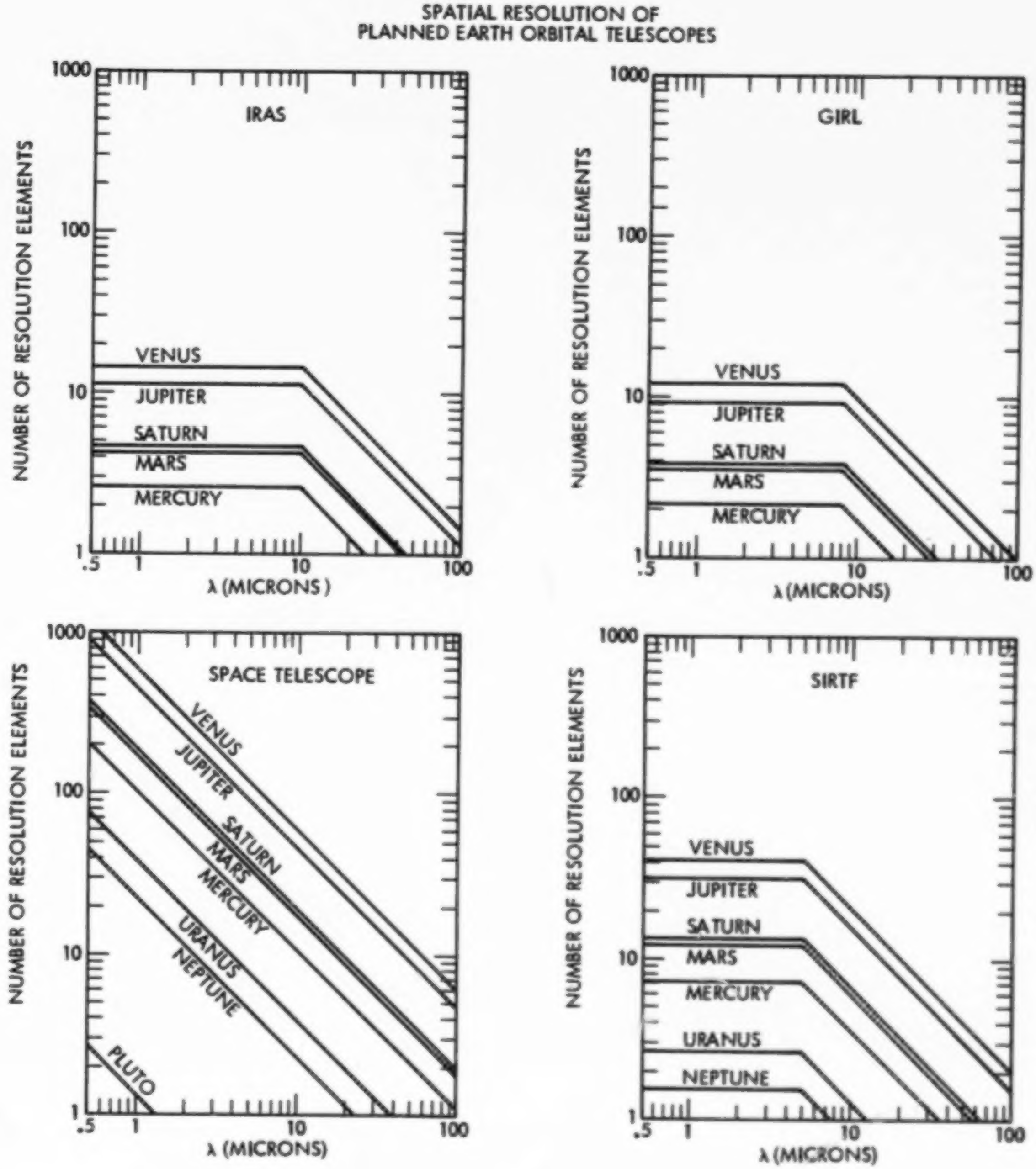
BEST DOCUMENT AVAILABLE

Table D-1. Planned Earth Orbital Platforms Relevant to Infrared Planetary Research

Platform	Tel. Size (m)	Focal Ratio	Tel. Temp	Focal Plane Temp	Infrared Instruments	Wavelength Range (μm)	$\frac{\lambda}{\Delta\lambda}$	Field of View (arcsec)	Pointing Stability (arcsec)
IRAS	0.6	f/9	8 K	3 K	Survey Array	5-8	2-2	240	20
					Survey Array	8-15	1.6	240	
					Survey Array	19-30	2.2	240	
					Survey Array	40-80	1.5	240	
					Survey Array	80-120	5	240	
					Low Resolution Spectrometer	6-24	20	240	
GIRL	0.4	f/10	5 K	2 K	Camera	8-120	1	540	3
					Photopolarimeter	5-250	10	6-420	
					Low Resolution Spectrometer	2-30	1500	6-60	
					Low Resolution Spectrometer	30-160	175	6-60	
					High Resolution Spectrometer	2-120	10000	30-300	
ST	2.4	f/24	294 K	(1)	None in first complement	.115-1000			.007
SIRTF	0.85	f/24	20 K	2 K	AO in Progress (2)			1.5-420	0.25
EOP	<0.5				Open to Experimenter				60 + Experiment Control

Notes:

(1) Provision for venting cryogens has been made in the ST design.
(2) First complement will consist of two or three relatively simple instruments.



SPATIAL RESOLUTION OF PLANNED EARTH ORBITAL TELESCOPES

Fig. D-1. Spatial resolution (number of resolution elements across planetary diameter) for four planned Earth orbital telescopes. The diffraction-limited regime results in the sloping portions of the curves, while telescope figure produces the flat portions.

IRAS (1983)

IRAS, the Infrared Astronomy Satellite, is an earth-orbiting, low-background, 60 cm diameter, survey telescope. Its mission is to map the entire sky in four infrared bands covering most of the 8 to 120 micron range with high sensitivity and to make special photometric and spectroscopic observations of selected sources. Much of the sky will be covered many times, offering the opportunity to detect faint asteroids. It will be launched late in 1983. It is expected to operate for one year.

The telescope is a f/9.17 system cooled by superfluid helium. The focal plane consists of an infrared survey detector array, visible star aspect sensors, a low resolution spectrometer and a totally chopped photometric channel.

The infrared survey array consists of 62 detectors covering four spectral bands. The total width of the field-of-view is 30 arcmin. The detector array is 7 detectors wide so that each detector covers a 4 arcmin angular width. Any real source is detected twice in each wavelength band to provide additional positional resolution as well as elimination of spurious detections.

The four spectral bands (detector materials) of the survey array are 8-15 microns (Si:As), 19-30 microns (Si:Sb), 40-80 microns (Ge:Ga), and 80-120 microns (Ge:Ga). In each band the sensitivity is 10^{-19} W/cm^2.

Locations of the IR sources will be provided to an accuracy of about 33 arcsec.

In addition to the infrared survey array and the visible light positional sensors, the focal plane of IRAS includes a 6-24 micron spectrometer with 5% resolution, a 5-8 micron channel and a 2-band, cold-blade-chopped photometric channel covering the 45-120 micron range.

References:

1. van Duinen, R. J., "Infrared Astronomical Satellite (IRAS)," in Infrared and Submillimeter Astronomy, G. Fazio, Ed., D. Reidel, Boston, Mass. 1977.

2. Aumann, H. H. and Walker, R. G., "Infrared Astronomy Satellite," Optical Engineering, Vol. 16, p. 537, 1977.

3. McCreight, C. R., Walker, R. G., and Witteborn, F. C., "IRAS and SIRTF: Implications of Scientific Objectives on Focal Plane Sensitivity Requirements," SPIE 132: Utilization of Infrared Detectors, 1978.

GIRL (1984)

The German Infrared Laboratory (GIRL) is a 40 cm liquid helium cooled f/10 telescope to be launched on Spacelab flight(s) to begin in 1984. The instrument complement is: 1) an 8-120 μm camera with 9' x 9' Field of View (FOV); 2) a 5-250 μm photopolarimeter (λ/Δλ = 10) with 6" to 420" FOV; 3) an Ebert-Fastie spectrometer (λ/Δλ = 1500 in the 2-30 μm range, λ/Δλ = 175 in the rejection are to be consistent with the use of detectors of unit quantum efficiency operating with noise-equivalent powers of 10^{-17} W/Hz$^{1/2}$ over a 1 arc minute field-of-view in a wavelength (λ) band up to 0.5 λ. Under such conditions, sensitivity is expected to be limited by fluctuations in zodiacal emission for λ near 10 microns. Limiting sensitivity in a diffraction-limited FOV, in a 2.5 micron band centered at 5 microns is expected to be about 10^{-30} W/m^2/Hz after 20 minutes of integration.

The anticipated SIRTF budget may be able to provide only two or three simple focal plane instruments in early flights. Space and interfaces for more (up to six) instruments will be available. More sophisticated instruments may be added as funding permits. The first Announcement of Opportunity for focal-plane instruments was postponed to 1982. A Phase B Study for SIRTF is expected to start in 1983, followed by Phase C/D (final design and fabrication) starting in 1984.

Further information on SIRTF is available in the following documents and references therein:

1. SIRTF Shuttle Infrared Telescope Facility, Report of the Focal Plane Instruments and Requirements Science Team and the SIRTF Science Working Group, November, 1979 (available on request from: SIRTF Science Group, N-245-6, NASA-Ames Research Center, Moffett Field, CA 94035).

2. SIRTF Design Optimization Study: Final Technical Report, Perkin-Elmer Corp., Contract NAS2-10066, Sept. 30, 1979.

3. Witteborn, F. C., Young, L. S., Miller, J. H. "Design Alternatives for the Shuttle Infrared Telescope Facility" SPIE 183 - Space Optics (1979) p. 24.

EOP (Planned)

NASA has devised an approach to space experimentation called the Experiments of Opportunity Payloads (E.O.P.) program. The program will use small standardized and self-contained packages that are deployed from Shuttle in near-Earth orbit and retrieved some days later.

The package will be a box about 75 x 75 x 150 cm weighing up to 500 Kgm and is provided with only a crude cold-gas thruster system for triaxial orientation. Coupled to inertial and optical sensors, pointing to ~ 1 arc minute is available. There are no Shuttle interfaces, no telemetry and only battery power (~ 10 kwh at 28 V dc). Data logging is performed with on-board recorders (10^{10} bits). All thermal control is passive.

This simplicity is at once the strength and weakness of the approach. With no outside connection, one avoids the difficulties of meeting interface requirements (the finished package must be judged safe). The defects are: the size, weight and power are limited; the box pointing is crude--fine guidance would need to be provided internally by the experimenter; the program is one of opportunity--one flies at no more than a few days' notice at random intervals so the experiment cannot require much pre-flight preparation nor be time-critical.

Further details can be obtained from David Shrewsberry at Goddard Spaceflight Center.

30-160 μm range) with 6" to 60" FOV; 4) a Michelson Interferometer ($\lambda/\Delta\lambda$ = 10000 in the 20-120 μm range) with a 30" to 300" FOV. Its first flight is wholly dedicated to astronomy and Earth aeronomy; later flights (if funded) may provide opportunities for observations of planetary atmospheres. Despite poor spatial resolution, this complement of instruments can provide significant improvements in our knowledge of Uranus' and Neptune's temperature, composition, and thermal balance, and allow some previously unexplored spectral regions to be investigated for Jupiter, Saturn, and Titan.

Further information is available in: "Optical and Infrared Telescopes for the 1990's," Vol. I, A. Hewitt, ed., Kitt Peak National Observatory Conference Proceedings (1980).

ST (1985, Refurbished in 1987-8)

The Space Telescope (ST) is a 2.4 meter diameter f/24 ambient temperature instrument in low earth orbit. The first complement of instruments includes no infrared experiments (although the CCD wide field/planetary camera will function to 1.1 microns). Provisions for stored, vented cryogens for cooled IR instruments have been made, and opportunities may exist through the AO process to operate an infrared instrument on ST in the late 1980's. The space telescope is designed for diffraction limited performance at 0.52 microns.

References:

The Space Telescope, NASA SP-392, 1976, U. S. Government Printing Office, Stock Number 033-000-00644-6.

Scientific Research With the Space Telescope, NASA CP-2111, 1980, U. S. Government Printing Office.

SIRTF (1989)

The Shuttle Infrared Telescope Facility (SIRTF) will be a reflyable, multiple-instrument, cooled, infrared telescope for use on Spacelab. The focal-plane will incorporate 2 or more instruments such as photometers, faint object spectrometers, and high-resolution spectrometers. They will be used for a variety of astronomical studies ranging from extragalactic to outer solar system objects. Specific focal-plane instruments and observational objectives will be selected by the usual Announcement of Opportunity process. SIRTF will be operated from Spacelab on flights starting in 1989 and repeated at 9 to 12 month intervals thereafter. Each flight will last from 7 to 30 days. The telescope is being designed for best performance in the 2 to 200 micron range, although it is expected to be capable of accommodating studies from 1 to 1000 microns.

The baseline design incorporates an 85 cm clear aperture in a Cassegrain optical system. The mirrors, baffles, and focal plane are cooled to below 20 K. Portions of the focal plane will be near 2 K. The secondary mirror may be oscillated at frequencies up to 20 Hertz with amplitudes as large as the unvignetted field-of-view which is at least 7 arcminutes in diameter. The image quality will be diffraction limited at 5 microns. Pointing jitter is t be no more than 0.25 arcsecond rms. Baffle and mirror temperatures and off-axis

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16. Abstract

This report contains the results of the deliberations of the Infrared Experiments Working Group. Its function was:

1) To evaluate the role of 0.5-300 micron remote sensing in planetary atmospheres exploration;

2) To identify key areas of infrared instrumentation requiring development for the investigations of atmospheres;

3) To provide the Planetary Programs Office with a framework within which such developments might be undertaken;

4) To document the state-of-the-art.

The approach used was to assess the value of a broad range of measurment techniques for the investigation of atmospheric phenomena, including quantitative intercomparisons of existing and planned instruments by a phenomenological method: given a particular measurement goal (e.g., composition and abundance, temperature structure, cloud and aerosol, etc.), what technique could, if properly developed, investigate the phenomenon? The charter of the group was limited to consideration of spaceborne and planetary probe instrumentation, principally for atmospheric investigations. The applicability of such instrumentation to the study of surfaces, comets and extended atmospheres was, however, included.

17. Key Words (Suggested by Author(s))
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